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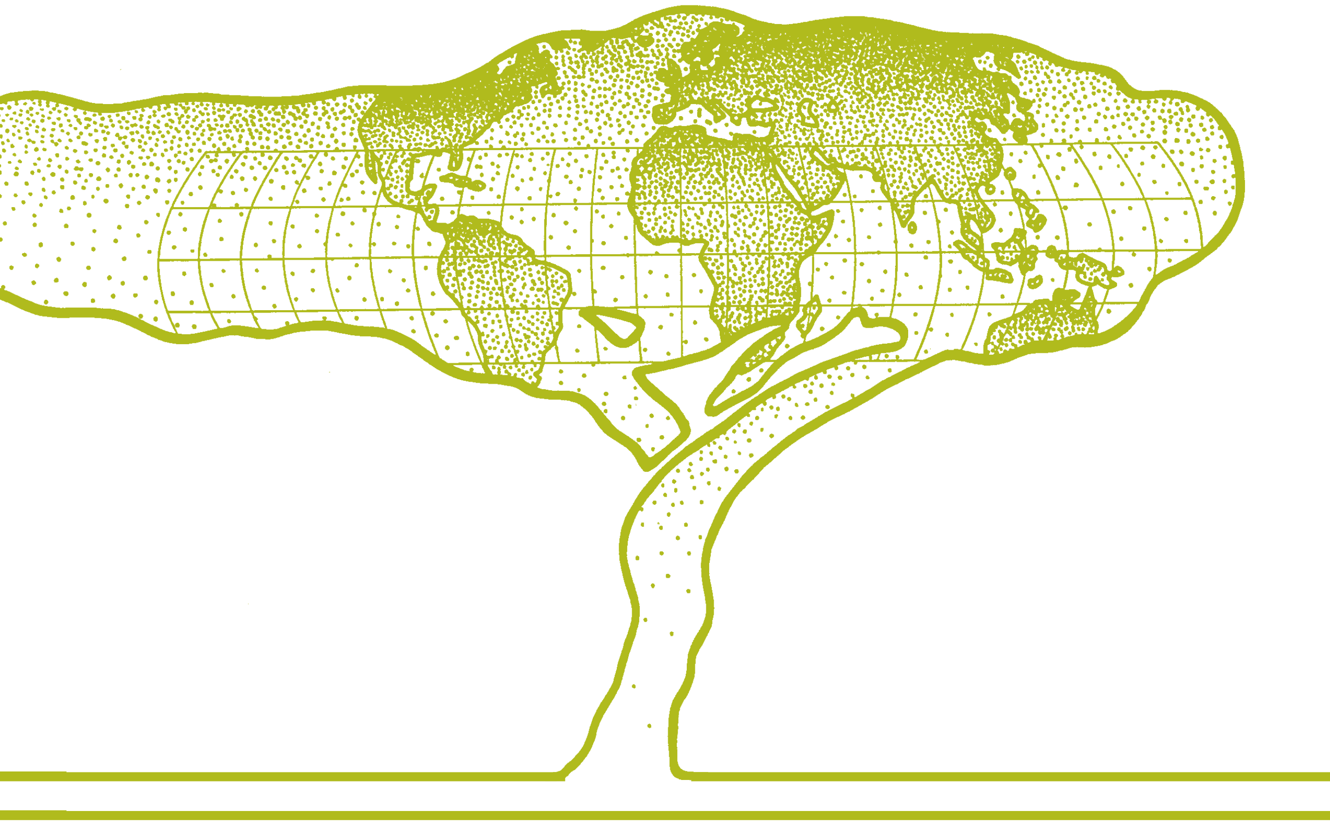

Mustafa Kamil Mahmoud FAHMI

Climate, trees and agricultural practices: Implications for food security in the semi-arid zone of Sudan

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Climate, trees and agricultural practices: Implications for food security in the semi-arid zone of Sudan

Mustafa Kamil Mahmoud FAHMI

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ABSTRACT

Livelihoods are precarious in arid and semi-arid regions, such as Sudan, as the main food crops are often grown in production systems that heavily depend on climatic conditions and appear to be threatened by several factors. Over 70% of Sudanese are farmers who rely mainly on rain-fed agriculture to secure their livelihoods. Their crop cultivation is constrained by such factors as climate change and variability, as well as low soil fertility, which is aggravated by limited agricultural inputs. Indigenous legume trees, such as acacias, can potentially alleviate the vulnerability of these systems. In practice this is possible by integrating trees with agricultural crops on the same piece of land, thus forming an agroforestry system. Nevertheless, the adoption of agroforestry also remains constrained by several factors, including unclear tree tenure and small farm size.

The main objectives of this research were: (I) To classify and compare various land-use systems so as to facilitate an analysis of the socio-economic impacts of farming practices in the semi-arid zone of Sudan; (II) To define the determinants and constraints for agroforestry based on the integration of natural acacia trees with agricultural crops, thus forming the agroforestry parkland system in Sudan; (III) To identify and analyse the main factors underlying the variability of crop yields during the period 2001–2010; and (IV) To characterize the impact of land-use changes between 1972 and 2010 on natural forests and land productivity.

The research was conducted at two distinct sites, El Dali and El Mazmum in Sennar state, Sudan (latitudes 12° 5′ and 14° 7′ N and longitudes 32° 58′ and 34° 42′ E, respectively). Principal data on households and crop yields were collected from 281 randomly selected households in face-to-face interviews using a pre-structured questionnaire. Soil and rainfall data along with satellite images were obtained from associated institutions in Sudan.

Qualitative and quantitative methods were used to analyse crop and household data, and the Excel template MAKESENS was used to study the rainfall data. GIS software applications and economic analysis were used in clarifying land-use changes and crop profitability with various land-use systems, respectively.

Agroforestry parklands that consist of the integration of acacia trees with agricultural crops were found to financially be the most profitable system, offering higher crop yields than monoculture systems. The number of people in a household, agro-ecological location, incentives from agricultural associations, and land holding size were the main drivers for farmers to combine acacia trees with agricultural crops, forming an agroforestry parkland system. Constraints for practicing agroforestry included insecurity of tree ownership, poor interaction between farmers and extension agents, lack of tree planting materials (in cases where a farmer would have adopted tree planting as a method to increase the tree cover), uncontrollable livestock movements on farms, and land owners' preference to rent their entire holding to landless farmers. The yields of most of the studied crops (sorghum, pearl millet and sesame) were affected by inter-annual variability in rainfall rather than agricultural practices. Land use and land cover have remarkably changed over time, resulting in a negative impact on soil properties and crop performance.

This research concludes for the region now studied in Sudan that climatic variability, low soil fertility and inadequate agricultural inputs contribute to a decline in crop yields. The lack of an appropriate tree tenure regime constitutes the strongest disincentive factor inhibiting farmers from practicing agroforestry, obviously the best available land-use option for sustainable crop cultivation and securing rural livelihoods.

Key words: Sudan, livelihoods, rain-fed agriculture, agroforestry parklands, crop yields, climate change and variability, tree tenure, acacia trees

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ABSTRACT IN ARABIC

تتميز سبل كسب العيش في الأقاليم الجافة وشبه الجافه، كما هو الحال بالسودان ، بالمخاطر حيث تزرع المحاصيل الغذائية الاساسية غالبا في نظم انتاج تعتمد اساسا علي الأحوال المناخية وتبدو مهددة بعدة عوامل. اكثر من 70 % من المزارعين بالسودان يعتمدون علي الزراعه المطرية لتامين سبل العيش. إلا أن زراعة محاصيلهم مقيدة بعوامل مثل تغير المناخ وتقلباته وانخفاض خصوبة التربة التي تتفاقم باستخدام محدود للمدخلات الزراعية. ربما تخفف الأشجار البقولية المحلية، مثل الاكيشيا (الشوكيات)، هشاشة هذه النظم. عمليا يتم ذلك بدمج الأشجار مع المحاصيل الزراعية في نفس الرقعة الزراعية، وتشكيل نظام التشجير الزراعي. ولكن، ان تبني نظام التشجير الزراعي يواجه عدة صعوبات تتمثل في عدم وضوح نظم ملكية الأشجار وصغر مساحات المزارع.

يهدف هذا البحث بشكل رئيسي الي: (1) تصنيف ومقارنة نظم استخدامات الأرض المختلفة لتسهيل تحليل التأتيرات الإقتصادبة-اجتماعية للممارسات الزراعية في الأقليم شبه الجاف بالسودان، (2) تحديد المحددات والمعوقات للتشجير الزراعي الذي يؤسس علي تكامل اشجار الاكيشيا الطبيعية مع المحاصيل الزراعية لتشكل نظام التشجير الزراعي التقليدي في السودان، (3) تحديد وتحليل العوامل الرئيسة التي تؤسس للإختلاف في انتاجية المحاصيل خلال الفترة 2001-2010، و (4) تشخيص تاثير تغيرات استخدام الأرض بين 1972 و 2010 علي الغابات الطبيعية و انتاجية الأرض.

أجري البحث في موقعين مختلفين، الدالي والمزموم بولاية سنار، السودان (دوائر عرض ′5 °12 و ′7 °14 شمالا وخطوط طول ′58 °32 و′42 °34 شرقا، علي التوالي). جمعت البيانات الأساسية للأسر و انتاجية المحاصيل من 281 اسرة، تم اختارها عشوائيا، بواسطة المقابلة الشخصية باستخدام استبيان معد مسبقا. تم الحصول علي بيانات التربة والأمطار والصور الجوية من المؤسسات ذات الصلة بالسودان.

استخدمت طرق نوعية وكمية لتحليل بيانات انتاج المحاصيل والأسر، بينما استخدم برنامج التحليل المسمي ب Excel MAKESENS لدراسة بيانات الأمطار. استخدمت تطبيقات نظم المعلومات الجغرافية GIS والتحليل الإقتصادي لتوضيح تغيرات استخدامات الأراضي وربحية المحاصيل لنظم استخدامات الأراضي المختلفة، علي التوالي.

أظهرت النتائج ان نظام التشجير الزراعي التقليدي الذي يتألف من دمج اشجار الاكيشيا مع المحاصيل الزراعية الأكثر ربحية مالية لتحقيقه انتاجية محاصيل اعلي مقارنة بالنظم الاخري احادية المحصول. عدد افراد الأسرة، الموقع الجغرافي، حوافز الجمعيات الزراعية ومساحة المزرعه هي الدوافع الاساسية للمزارعين لدمج اشجار الاكيشيا مع المحاصيل الزراعية لتكوين نظام التشجير الزراعي التقليدي. معوقات تبني نظام التشجير الزراعي تضم عدم ثبات ملكية الأشجار، ضعف التفاعل بين المزارعين والمرشدين، غياب مواد زراعة الأشجار، عدم ضبط حركة الحيوان في المزارع و تفضيل ملاك الأراضي ايجار مساحة اراضيهم الكلية للمزارعين الذين ليس لديهم اراضي زراعية. انتاجية معظم المحاصيل قيد الدراسة (ذرة، دخن، سمسم) تأثرت بالإختلاف في الهطول السنوي عوضا عن الممارسات الزراعية. تغير بمستوي ملحوظ استخدام الأرض وغطاء الأرض خلال الفترة الزمنية وأدي ذلك الي حدوث تأثيرات سالبة في خصائص التربة وأداء المحاصيل.

هذا البحث استنتج للاقليم الذي اجريت فيها الدراسة الان بالسودان الي مساهمة التغيرات المناخية و انخفاض خصوبة التربة وعدم كفاية المدخلات الزراعية في تدني انتاجية المحاصيل. يشكل عدم وجود نظم لضمان ملكية الأشجار العامل الأهم لتثبيط المزارعين من ممارسة نظام التشجير الزراعي، والذي من الواضح يعد أفضل خيار متاح لاستعمالات الارض لإستدامة الانتاجية الزراعية وتامين سبل العيش للمجتمعات الريفية.

الكلمات الدالة: السودان، سبل العيش، الزراعة المطرية، التشجير الزراعي التقليدي، إنتاج المحاصيل، تغير المناخ وتقلباته، حيازة الاشجار، إشجار الاكيشيا

PREFACE

I am overjoyed and relieved that the results of my research are now published in line with the aims of the socio-economic part of the research project "Carbon Sequestration and Soil Fertility on African Drylands" (CASFAD)" funded by the Academy of Finland. Much time has already passed since my joining this project in 2010. However, my ultimate dream was always to find solutions for the food insecurity in my home country, Sudan, and to contribute to improving the livelihoods of some 40 million people, the majority of whom still live under the poverty line. The study was also, at an advanced stage, supported financially by a VITRI-led component of the "Building Biocarbon and Rural Development in West Africa" project (BIODEV) financed by the Finnish Ministry for Foreign Affairs, as well as by the Mikko Kaloinen Foundation and the University of Helsinki in Finland, and the University of Khartoum in Sudan.

I would like to express my sincere gratitude to all my supervisors. My grateful and enormous thanks go first to Professor Olavi Luukkanen, my initial supervisor and CASFAD project leader, for continuously supporting me during both my MSc. and my PhD. studies and related research since 2007, when I first visited Finland and VITRI as an exchange student. His guidance and immense knowledge helped me in all my research and the writing of this thesis and its individual scientific articles. I am also grateful to my main supervisor Professor Markku Kanninen for his guidance, advice, encouragement and insightful suggestions on this work. His pertinent comments and questions led me to expand my research to new approaches and to looking at it from different perspectives. I am, too, greatly indebted to my supervisors and co-authors in Sudan: Assoc. Professors El Amin Sanjak, Abdalla Mirghani and Dafa-Alla Mohamed, for their assistance, insights and stimulating discussions, as well as for the sleepless nights we were working together to keep deadlines. All of them have offered excellent guidance and valuable inputs to my whole thesis.

My deep thanks and supplications go to the late Assoc. Professor Huda Sharawi, a previous supervisor to this work and the first person who had forwarded to me the news of a possibility to join the CASFAD project as a doctoral student. Before she passed away, we had long discussions related to my academic dissertation – may Almighty Allah rest her soul in paradise. I am also grateful to Dr. Kalame Fobissie, for guidance and nice work together during the writing the first paper. I would like to sincerely thank the pre-examiners of my thesis, Professors John Sumelius and Martti Esala, for their comments and suggestions that made the final result look different.

At VITRI and the Department of Forest Sciences I have met with many people who come from different countries; with them I used to share everything possible or impossible, and we were living together for many years next to piles of snow, but peacefully and friendly. Without giving all the names, I greatly appreciated their company. Specifically, my thanks go to Dr. Hannu Rita and Jarkko Isotalo for the help in matters related to statistical analysis. My unique acknowledgement goes to respected Dr Jukka Lippu who made my live easier in Finland. At the department of Agricultural Sciences I would like to thank my brothers Biar Deng and Dr. Hany El Sayed who supported me throughout the course of this work. Furthermore, it would be remiss of me not to direct my thanks to Stella Thompson for her language checking of papers as well as the thesis summary. In the same way, I would like also to thank my colleague Ibrahim Toure for his help in improving the text in some parts of my thesis.

Acknowledgements are also due to all professionals at the Forests National Corporation (FNC) in Khartoum and in Sennar state, and to the Ministry of Agriculture, Animal Wealth and Irrigation of Sennar state for the crucial rainfall data. Similarly, at the Remote Sensing Authority

(RSA) in Khartoum, from my heart I wish acknowledge with numerous thanks Dr Mohammed Osman, Mohaned El-Tijani and Tameni Ahmed for the unique data on land use and land cover change, as well as the maps of the study area. I am extremely grateful to all my colleagues at the Faculty of Forestry, University of Khartoum in Sudan, who have supported me along the way.

A special thank also goes to Ali Sheikh Idris, senior staff at FNC, Sennar state, who made all the village leaders prepared to meet me and also made a great effort to facilitate my field data collection and provide supplementary information as required. Similar thanks go to Ahmed Hamed for his kind hospitality during data collection at El Dali, and to all agricultural and forest inspectors I met at El Mazmum. I am sincerely grateful to all the village leaders who gave me permission to conduct this research. I highly appreciate the contributions from all persons, including the farmers interviewed, who were involved in this research, for their information, time and hospitality during data collection.

I am highly grateful to my siblings Mona, Hagir, Ismail, Mahmoud, Hassan and Mutwakel for the patience and enduring emotional support with *Duaa*, which indeed encouraged and helped me to complete this work. Finally, I try to do the best in thanking my dearest companion Enass Salih. She has shown unbelievable strength and patience in taking care of our children Tala, Ahmed and Sama Fahmi, along with other home tasks, while still carrying out her own interdisciplinary doctoral study research and sharing her time between VITRI and the Faculty of Pharmacy on the Viikki campus. I wish her from my deep heart a fruitful completion of her doctoral studies in a little while.

This work is dedicated to the souls of my parents.

Helsinki, July 2017
Mustafa Kamil Mahmoud FAHMI

CONTRIBUTIONS

This dissertation is based on the following original scientific papers:

I. Fahmi, M.K.M., Dafa-Alla, M.D., Kanninen, M. & Luukkanen, O. 2016. Impact of agroforestry parklands on crop yield and income generation: case study of rainfed farming in the semi-arid zone of Sudan. Agroforestry Systems, first online 1-16 (DOI 10.1007/s10457-016-0048-3).

II. Fahmi, M.K.M., Sanjak, E., Kanninen, M., Luukkanen, O., Kalame, F.B. & Eltayeb, A.M. 2015. Determinants and constraints of integrating natural acacias into mechanised rain-fed agricultural schemes Sennar State, Sudan. GeoJournal 80(4): 555–567.

III. Fahmi, M.K.M., Sanjak, E., Kanninen, M. & Luukkanen, O. Impacts of meteorological drivers and agricultural practices on sorghum, millet and sesame yields in semi-arid lands in Sudan. Journal of Natural Resources and Environmental Studies 5(1): 1–11.

IV. Fahmi, M.K.M., Sanjak, E. & Luukkanen, O. Land use and land cover changes in semi-arid Sudan and their impacts on natural forests and cropland productivity (Submitted).

Mustafa Fahmi presented the research idea and methods of data collection in each paper (I–IV). Mustafa Fahmi also made a reconnaissance survey of the study area and prepared the final form of the research questions together with El Amin Sanjak. He then collected and analysed the entire data required for all papers. In study I, Mustafa Fahmi analysed the economic data together with Dafa-Alla Mohammed. In studies II & III Mustafa Fahmi analysed the social and metrological data together with Fobissie Kalame and Markku Kanninen, respectively. In study IV data on land use and land cover changes were obtained by Mustafa Fahmi. In all papers (I–IV), Mustafa Fahmi wrote the first draft of the manuscripts, which were reviewed and modified in several stages by the other respective authors.

LIST OF ACRONYMS AND ABBREVIATIONS

Anon.	Annual Crop and Food Supply Assessment Mission
CBoS	Central Bank of Sudan
CBS	Central Bureau of Statistics
FAO	Food and Agricultural Organization of the United Nations
FAOSTAT	FAO-Statistical Databases
FCPF	Forest Carbon Partnership Facility
FNC	Forests National Corporation
GDP	Gross Domestic Product
GIS	Geographic Information System
HRS	Household Responsibility System
ICRAF	The World Agroforestry Centre
IFAD	International Fund for Agricultural Development
MAAWI	Ministry of Agriculture, Animal Wealth and Irrigation
NAPA	National Adaptation Programme of Action
PRB	Population Reference Bureau
RSA	Remote Sensing Authority
RSSS	Rangeland Sector of Sennar State
SIFSA	Sudan Integrated Food Security Information for Action
SSA	Sub-Saharan Africa
SSZ	Sudano-Sahelian Zone
UN	United Nations
UNEP	United Nations Environment Programme
USAID	United States Agency for International Development
WPR	World Population Review

TABLE OF CONTENTS

1. Introduction

1.1. People, climate and livelihoods in arid and semi-arid zones

Arid and semi-arid zones, where rain-fed agriculture is practiced under risky annual rainfall, are home to nearly 700 million people, and cover approximately one-third of the earth's land surface (Venkateswarlu and Shanker 2012, Bose 2015, Schmidt and Pearson 2016). These zones include most regions in western Asia and northern Africa, which have experienced unprecedented challenges such as climate change and variability, long spells of drought and land degradation. The preceding factors also adversely impact agricultural production-based livelihoods. Agricultural production constitutes the primary source of food and income for the local people in these zones (Sivakumar et al. 2013, Mwadalu and Mwangi 2013, Selvaraju 2013, Ehui and Pender 2005). In addition, some 280 million tonnes of potential cereal production in many areas of Asia and Africa are still under threat of loss due to climate change (Singh et al. 2013).

Food insecurity, decreased income per capita and loss of soil fertility combined with land degradation are the ongoing scenarios in Africa (Vlek et al. 2010, Mbow et al. 2014b). At the global level, the human population is predicted to increase about 50 percent by the end of 2050. Concurrently, this will lead to a twofold increase in world food demand to attain food security and the delivery of food for ca. one billion hungry people (Green et al. 2005, Holmgren 2012). Climate change, rainfall variability in particular, is one of the major potential constraints in achieving tomorrow's food security. Rainfall variability poses a substantial threat in managing subsistence systems that depend on ecological factors (Lemos et al. 2012, Sivakumar et al. 2013). Accordingly, arid and semi-arid zones are more vulnerable to rapid changes in annual rainfall (Narisma et al. 2007). Contrastingly, such changes in climate may lead to benefits, for example, enhancing livelihoods and environmental security through improving crop, soil and water management practices or by using stress-tolerant crops to reduce the potential impact of predicted climate change (Dar and Gowda 2013).

Considerable evidence also suggests that climate change will largely impact agriculture in Africa and its future development (cf. Kurukulasuriya et al. 2006, Mohamed 2011). As a result of this, rain-fed agricultural systems in many areas of the Sudano-Sahelian zone (SSZ), comprising17 African countries including Sudan, have already come under the threat of climate change (Mertz et al. 2009, Karlson and Ostwald 2016). More generally, climate change places a fundamental limitation on those small-scale farmers that rely entirely on rainfall to cultivate their subsistence crops merely for food security (Traore et al. 2014). In fact, a general consensus in opinion exists that small-scale farmers are in the front lines and more vulnerable to environmental and climatic variability (Lasco et al. 2014). Climate change also threatens traditional agroforestry parkland systems that are largely practiced in many African dryland zones where sorghum (*Sorghum bicolor* (L.) Moench) is the main food crop (Coulibaly et al. 2014).

Based on an earlier similar definition by Reutlinger (1985), the World Bank (1986) defined food security as "*access by all people at all time to enough food for an active and healthy life*". This definition consists of two important points; 1) adequate food at all times and, 2) the ease of acquiring it. The definition concurrently sheds light on constraints that might be tied to food security such as accessibility to adequate food at all times. Livelihood diversification is accordingly one of the most important adaptation strategies for Africa's poorest people for inflating their income portfolios (Elmqvist and Olsson 2006, Mertz et al. 2009, Ibnouf 2011, Belachew and Zuberi 2015). In view of this, livestock husbandry often integrates with agricultural crops on farms as a secondary source of income, together commonly forming agro-pastoral or agro-silvo pastoral management regimes.

1.2. Sudan as an example of semi-arid countries

The total area of Sudan is approximately 1.9 million km^2. The country lies in the northeast of the African continent, between latitudes 14° and 22° N and longitudes 22° and 38° E (Eltoum et al. 2015, Daur et al. 2016). In 2014, the World Population Review (WPR) and the Population Reference Bureau (PRB) estimated the total population of Sudan at approximately 39 million people. The last reference (PRB 2014) expected the population to increase to some 55 and 77 million capita by mid-2030 and mid-2050, respectively.

The secession of South Sudan from Sudan (former) in 2011 has led to an approximately 25% cut in its total area, and decreases of 24%, more than 70% and nearly 30%in total population, vegetation cover and total potential arable land, respectively (Mahomed 2011, Ahmed et al. 2012). It is worth mentioning that the arable land in the country prior to the secession covered approximately 86 million hectares (ha), only 20% of which is utilized for crop-production purposes (FAO 2015b).

Post-July 2011, Sudan was re-classified into five distinct climatic zones by the Remote Sensing Authority (RSA) of Sudan and the FAO SIFSA project (Sudan Integrated Food Security Information for Action): hyper-arid, arid, semi-arid, dry sub-humid and moist sub-humid (Fig. 1). Disparities between such ecological zones are striking, as each one is characterized by certain climatic conditions, soil structure and vegetation cover. In this context, the country spans from a hyper-arid zone in the far northern desert, where annual precipitation is less than 100 mm, to dry sub-humid and moist sub-humid zones in the far south, where mean annual rainfall exceeds 800 mm (Elagib 2011b, Abdelmalik et al. 2015). During summertime, temperatures potentially reach up to 40º C in the northern part of the country but during the dry-winter time may possibly decrease to less than 10º C in the same zone (Fadel-El Moula 2005, NAPA 2007). In general, the mean annual temperature varies between 26º and 32º C throughout the country (Zakieldeen 2009).

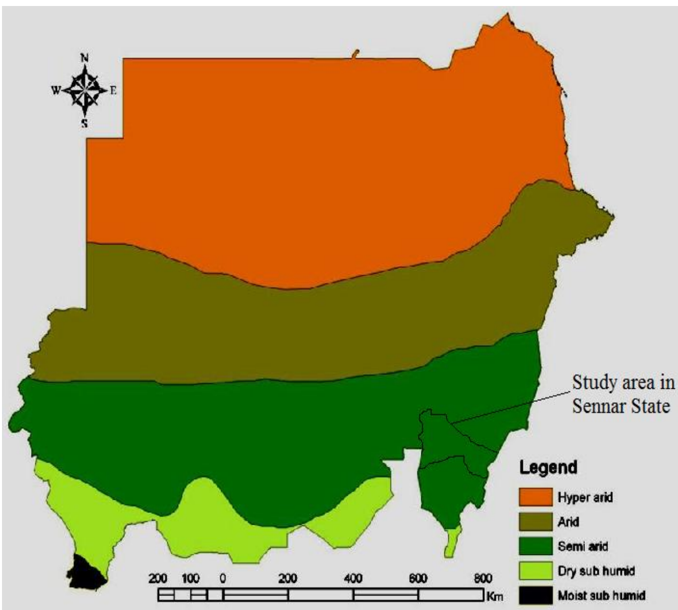

Fig. 1 Climatic zones of Sudan
Source: Modified from the Remote Sensing Authority, Sudan.

Arid and semi-arid zones located in central Sudan occupy approximately 60% of its total area; they are mostly flat surfaces with fertile lands. Agriculture and pastoralism are the main activities, and a variety of Sudanese staple and export crops are grown in a large-scale either under rainfall conditions or in irrigated agricultural schemes. Natural forests and woodlands also occur in the same zone, with acacias as the most dominant tree species (Muneer 2008, FAO 2015b).

The main agricultural systems in Sudan include irrigated, traditional and mechanized rain-fed farming. The last system covers a total area of some 6 million ha (Abbadi and Ahmed 2006). Traditional farming accounts for nearly 60% of the cultivated land and employs more than 60% of the population (Siddig and Babiker 2012). Moreover, the significance of this system is attributed to nearly 90% of rural Sudanese depending on it for securing their food and cash needs (Ibnouf 2009).

Agriculture in general constitutes one of the major national economic sectors in Sudan. During the 1960s it augmented more than 39% of Sudan's gross domestic product (GDP). In the early 2000s, due to favourable climatic conditions for agricultural crop requirements, the agricultural sector contributed by over 46% of the GDP (Abbadi and Ahmed 2006). However, during 2001, 2002, 2003 and 2004 the contribution of this sector has showed a clear decline in the Sudanese GDP by nearly 37, 35, 34 and 32%, respectively. Between 2005 and 2009 the contribution of agriculture to GDP has remained constant at about 31% (CBoS 2009, Siddig and Babiker 2012). During the 1980s the contribution of this sector to GDP experienced a substantial decline as a result of drought, which has been striking many agricultural areas in Sudan. The Central Bureau of Statistics (CBS) asserts that the percentage of the agricultural sector in Sudan's GDP has steadily declined over time as a result of declines in crop production caused by climate change and variability (Anon. 2015).

The main Sudanese agricultural crops grown to underpin food security include sorghum (*Sorghum bicolor* (L.) Moench), pearl millet (*Pennisetum glaucum* L.) and wheat (*Triticum aestivum* L.) (Sassi and Cardaci 2013a). Sesame (*Sesamum indicum* L.), cotton (*Gossypium hirsutum* L.), groundnut (*Arachis hypogea* L.) and sunflower (*Helianthus annuus* L.) are considered cash crops.

Sorghum is cultivated mainly in rain-fed farming with relatively higher rainfall or through irrigated agricultural schemes. It is considered a subsistence crop for the majority of rural Sudanese (USAID 2011). Traditional and mechanized rain-fed systems produce approximately 75% of the country's total sorghum output (Abbadi and Ahmed 2006). In addition, sorghum alone represents ca. 60% of the total cereal production needed for local consumption (Elmulthum et al. 2011). In sub-Saharan Africa (SSA), sorghum is commonly grown with millet on relatively large areas characterized by high variability in rainfall and simple agricultural inputs in general (Garí 2002, Singh et al. 2013). Despite this, the combined sorghum and millet harvest in 2012 accounts for ca. 40% of the total cereal harvested area, and 23% of the total grain production in the SSA (FAOSTAT 2013).

Historical records reveal that sorghum was first introduced to Egypt prior to 3000 B.C. (Mwadalu and Mwangi 2013). In Kenya and some areas in arid and semi-arid lands, sorghum in particular has the potential to deter food insecurity due to its ability to survive dryness and to grow in various types of soil (Mwadalu and Mwangi 2013). More importantly, sorghum together with wheat, rice and maize comprise the four major food crops used by nearly 500 million people still living in the semi-arid zones of Africa and Asia (Fetene et al. 2011). The cultivation area of sorghum and millet is expected to increase in the SSA, as these two crops show adaptation to climate change and variability (Sultan et al. 2013).

Sesame is an ancient oil crop cultivated globally in both tropical and subtropical areas along with the southern temperate zones of the Asian, African and South American landmasses (Ashri 1998, Bedigian 2003, Anilakumar et al. 2010). Sesame is also known as an "orphan crop" due to the lack of research related to its molecular genetics in past decades (Uncu et al. 2015). It is an important economic crop introduced to Africa decades ago from Asia (Bedigian 2013). According to FAO (FAOSTAT 2014), Myanmar is the leading country in terms of global sesame production, which is estimated at approximately 890 000 tonnes/year, tracked by India (636 000), China (588 000) and Sudan (562 000 tonnes/year). These four countries therefore produce ca. 68% of the total sesame production in the world (Bedigian 2003, Laurentin and Karlovsky 2006).

Sesame is extensively grown by Sudanese rain-fed agricultural farming. It has been considered one of the major economic pillars in Sudan, as it has significantly contributed to the economy (Abdellatef et al. 2008, 2010). In addition, sesame is also viewed as a main cash crop that has the potential to secure income for rural Sudanese (study II). At the national level, it is given much attention as an export crop, and has been the leading agricultural export product for many years. For example, the contribution of sesame to the total export revenues substantially increased from ca. US $ 223.5 million in 2012 to US $ 472.4 million in 2013, giving an increase of 111% (CBoS 2013).

1.3. Factors influencing the improvement of livelihoods in Sudan

Approximately 80% of the cereal crops in the Arab region, which is comprised of 22 countries, is produced in Sudan and Yemen. Nevertheless, hunger prevalence is still relatively high in these two countries, ca. 32% in Yemen and 21% in Sudan (FAO 2008, Haddad et al. 2011). National food security has been a prime goal in Sudan since 1956, when it became an independent country, with the aim to fulfill social welfare for people and political stabilization. However, since then several factors, such as droughts and political crises, have posed constraints to achieving this goal (Aldeshoni 2005, Ibnouf 2011, Chen et al. 2013, UNEP 2014). Moreover, enduring civil wars and conflicts in the Darfur, South Kordofan, and Blue Nile regions have significantly affected food security in the country (Mahgoub 2014, USAID 2014). Additional factors probably contributing to food insecurity in Sudan include land-use changes and environmental degradation, lack of water resources and extension services, inherited customs (reliance on the sole crop), land tenure, and lack of access to credit, technologies, agricultural inputs and meteorological data (Luukkanen et al. 2006, Ahmed et al. 2014, Ardö 2015, Ibrahim et al. 2015, Adam and Eltayeb 2016).

It is worth mentioning that more than two-thirds of the Sudanese people live in rural areas and depend predominantly on rain-fed agriculture to secure their annual food and income. Sorghum, millet, sesame and groundnut are the main crops cultivated under rainfall conditions for that purpose. As a result, the yields of these crops have been gravely affected by climate change and variability, especially the inter-annual variation of rainfall, in addition to other factors, e.g. poor soil fertility, lack of agricultural inputs (mainly herbicides and fertilizers) and tree tenure issues which have discouraged many farmers from integrating legume trees, such as acacias, with crops to establish farmland-based agroforestry systems.

1.4. Study aims and hypotheses

This dissertation was aimed at understanding the factors contributing to food insecurity in the semi-arid zones of Sudan, and to investigate the potential for integration of acacia trees with agricultural crops to form agroforestry systems to secure livelihoods and mitigate the vulnerability of local people to climate change, along with identifying the determinants, constraints and risk measures facing the livelihoods of farmers in this region.

Specific objectives were:

- ⇨ To classify and compare various farming systems, so as to analyse their socio-economic impacts on the livelihoods of local people (study I).
- ⇨ To describe the determinants and constraints associated with the practices of agroforestry parkland systems (study II).
- ⇨ To detect trends in relationships between annual precipitation, agricultural inputs and crop yields (study III).
- ⇨ To describe the effect of land-use and land-cover changes on soil properties and crop performance (study IV).

The hypotheses of this study were:

- ⇨ The financial returns of cultivation crop vary from land-use system to another, or from a farmer to another farmer (study I).
- ⇨ Farmers' perceptions of agroforestry practices are influenced by several potential factors, and they have insufficient knowledge concerning the role of agroforestry practices in improving sustainable livelihoods (study II).
- ⇨ Crop responses to inter-annual climatic variability combined with limited effects of agricultural inputs potentially lead to declining yields (study III).
- ⇨ Poor soil properties and low agricultural productivity can be explained by the removal of woody vegetation (study IV).

2. Theoretical framework and literature review

2.1. Schematic framework of the dissertation

The schematic framework of this dissertation focuses on literature related to issues influencing the insecurity and vulnerability of rain-fed agricultural systems in semi-arid drylands in general. These systems are managed by the majority of people with the purpose of securing their own household livelihoods. Current research focuses principally on issues brought up within the box in Figure 1, which is divided into two conceptual areas in the literature. The first part focuses on literature that elucidates the potential factors influencing the integration of trees with crops on farmlands to form agroforestry systems. These often include several factors such as land holding size, ecological zone and the level of environmental awareness. Research introduced in the same section also covers literature concerning the constraints confronting agroforestry systems such as tree tenure issues, lack of extension services, lack of awareness of the roles of trees on farms, and farm size.

The second part focuses on the major factors influencing land productivity and the variability of crop yields. According to the literature, the most significant factors are: (1) climate change and variability, especially the inter-annual variation of rainfall, (2) the type of land-use system being practiced (monoculture or agroforestry), (3) agricultural practices/technology (mainly herbicides, pesticides and fertilizers) and (4) the availability of agricultural inputs, credits and reliable rainfall data in particular.

In addition, the current study introduces literature discussing how agricultural expansion can influence the dynamics of natural vegetation cover. This issue is closely related to several topics discussed above such as tree tenure and land size.

The conclusions and recommendations suggested by this study have potentially implications for land-use policy development in semi-arid regions including Sudan. An underlying general aim of this work was to provide information for a new strategy and more sustainable land-use alternatives for reducing the vulnerability of cropland systems and, consequently, to improve the climate change adaptation of the affected rural communities in such regions.

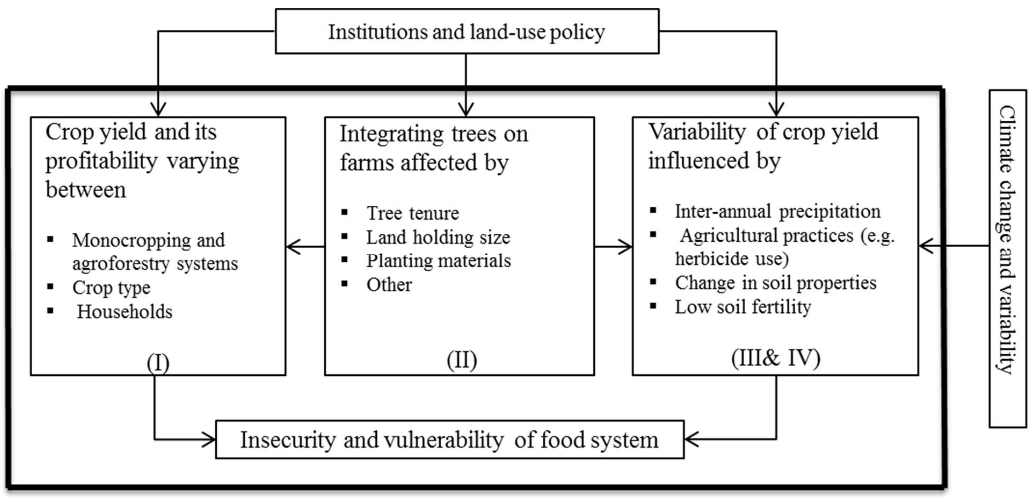

Fig. 2 Schematic framework of the study. The present study emphasizes issues within the bold box.

2.2. Determinants and constraints of agroforestry practices

Agroforestry has been redefined as "*a dynamic, ecologically based, natural resources management system that, through the integration of trees on farms and in the agricultural landscape, diversifies and sustains production for increased social, economic and environmental benefits for land users at all levels*" (Leakey 1996). In the SSA, scattered trees are considered a form of landscapes also known as agroforestry parkland systems, especially when they are formed on recently fallowed fields (Pullan 1974, Boffa et al. 2000). These scattered trees consist of various species that farmers retain and integrate with agricultural crops, such as sorghum and millet, the main two food crops in the semi-arid zone of Africa (Bayala et al. 2011). Agroforestry parkland is therefore characterized as a typical agricultural farming system managed by small-scale farmers in many areas of the African Sahel (Boffa 1999). It is also largely recognized as a system with the potential to consolidate the resilience of small-scale farmers to ongoing and future climate change risks (Lasco et al. 2014). Such systems may also have the potential to diversify production, improve soil fertility and local climate along with securing the food production of nearly 1.8 billion people in the developing countries at the very least (Nair 2007, Thangata and Hildebrand 2012, Mbow el al. 2014a).

In the arid and semi-arid tropics of Africa, agroforestry parkland systems are common and far-famed, comprising various tree species such as *Faidherbia albida* (Delile) A. Chev., néré (*Parkia biglobosa* (Jacq.) R. Br. ex G. Don) and acacia species (Nair et al. 1999, Bayala et al. 2011, Foli and Abdoulaye 2016). Some tree species, such as *Faidherbia albida* and baobab (*Adansonia digitata* L.), have significant roles in agroforestry parkland systems due to their potential to improve the soil fertility of cropping land and provide fodder to livestock (Sacande et al. 2016 in: FAO 2016). Trees are infrequently planted in agroforestry parkland and rather exist through natural regeneration, for instance, the néré grows at a density of ca. 2 to 3 trees ha^{-1} (Kater et al. 1992). In Malawi, about 18% of the basal area cover per hectare in parklands is occupied by *Faidherbia albida* (Beedy et al. 2016).

A number of studies (Depommier et al. 1992, Saka et al. 1994, Rhoades 1997) show the impacts of trees in agroforestry parkland systems on agricultural crop performance and soil improvement in general. For example, *Faidherbia albida* trees establish naturally in open areas or in parkland systems, leading to an increase of more than 100% in the maize crop yield in Malawi, and in increases of more than 35% and 120% in the sorghum yield in Ethiopia and Burkina Faso, respectively (Poschen 1986, Depommier et al. 1992, Saka et al. 1994). In addition to improving soil fertility, *Faidherbia albida* trees also show improvements in soil water retention and microclimate (Nair et al. 1999). To warrant this, declining soil fertility in the Masaka region of Uganda induces many farmers to adopt various types of agroforestry systems, where more than 70 species of trees belonging to families, such as Fabaceae, Moraceae, Euphorbiaceae, Combretaceae and Myrtaceae, are retained (Sebukyu and Mosango 2012).

The long-standing traditional agroforestry system in Jebel Marra in western Sudan is based on *Faidherbia albida* trees. The soil structure together with climatic conditions encourage sedentary pastoralists to integrate their staple millet crop with trees and thus ensure sustainable crop production or provide wood for energy and fodder for animals (Miehe 1986). However, the most important trees growing naturally in agroforestry parkland systems in central regions of Sudan include *Acacia senegal* (L.) Willd., *Acacia seyal* (Delile) and *Acacia mellifera* (Vahl) Benth., with relatively few *Balanites aegyptiaca* (L.) Delile and *Zizyphus spina-christi* (L.) Willd. (study II). More generally, agroforestry based on traditional natural resources management is considered a fruitful system in the drylands of Sudan (Ahmed et al. 2014). Especially the integration of agricultural crops with *Acacia senegal* trees on farmlands is considered to lead to improved land management, economic benefits from tree products (such as gum arabic) and decreased environmental and land degradation (Aymeric et al. 2014).

Agroforestry system practices are often influenced by several factors that may differ from one country, ecological zone and farm to another. To cite a few, Nkamleu and Manyong (2005) studied the impacts of socio-economic factors on the adoption of agroforestry systems in Cameroon. Dhakal et al. (2015) attempted to examine the rate of adoption of agroforestry-based land management practices and the main factors positively leading to the adoption of such systems in Nepal. In Pakistan, farmer's perceptions and household's characteristics constitute the main reasons encouraging farmers to adopt agroforestry systems (Irshad et al. 2011). Similarly, in arid and semi-arid regions of Northern Kordofan state of Sudan, the educational level, interaction between farmers and extension agents, land size, level of environmental awareness and social interactions seem to be factors affecting the adoption of agroforestry systems (Muneer 2008). In the case of India, the significance of trees for future generations positively encourages farmers to plant trees forming agroforestry systems (Sood and Mitchell 2009). In Kenya, some studies identify the potential factors leading to heterogeneity in agroforestry practices even between small-scale farmers (Nyaga et al. 2015). In light of the above, it is relevant to state that agroforestry constitutes an important land management option for the majority of people living in semi-arid regions (Syampungani et al. 2010).

In practice, the functional difference between agricultural and agroforestry systems most likely stems from the latter having the potential to maintain a flow of nutrients between its components (Nair et al. 1995). The simplicity of the adoption of "fertilizer trees" increases the willingness of farmers to adopt the system, so as to improve the soil fertility in their farmlands, farm productivity and livelihood in general. However, in many cases their willingness is constrained by several factors such as insecurity of tree or land tenure, lack of supporting materials (seeds, fuels, tractors etc.) and extension services, lack of basic knowledge concerning the roles of trees on farms, conflicts in animal control, and the educational level of farmers.

In many countries in the SSA, land or tree insecurity constitutes the fundamental constraint for adopting agroforestry systems such as agroforestry parklands (Poudyal 2009, Namubiru-Mwaura and Place 2013). This is also obvious in Sudan, where land ownership is the most important issue for the majority of rural inhabitants (Egemi 2006). In this particular country, customary law is still a form of land tenure. This implies that land ownership is not officially recognized as legal ownership by government courts (Komey 2009). Such customary law has three major constraints: "*uncollected, unrecorded and uncertain*" (Mahdi 1977, Egemi 2006, Komey 2009), despite Article 43 (1) in the Sudanese constitution stipulating that "every citizen shall have the right to acquire or own property as regulated by law". This clearly suggests that land tenure and natural resources, such as trees, can be officially registered by law under the status of ownable property (Eltayeb and Osman 2011).

Arguably, laws related to land tenure and land use in Sudan have no clear clauses on long-contested natural resource and land ownership problems. Such laws include the Land Settlement and Registration Ordinance enacted in 1925, the Land Acquisition Ordinance of 1930, and the Unregistered Land Act of 1970. The view is that e.g. the Land Settlement and Registration Ordinance (1925) enables anybody to claim a title or land right to a piece of land by registering the property either as a freehold or a leasehold under a common law principle (Egemi 2006). Consequently, such laws seem to have strengthened government power in grabbing lands. For example, the government has evicted many farmers from their lands in the Gadarif and Kassala states in eastern Sudan due to new leasehold titles (Eltayeb and Osman 2011).

For comparison, land in China is considered communally owned based on contracts, in which land ownership is distributed by village committees to individual households under the law of the household responsibility system (HRS) ratified in the 1980s. Since the 1990s, such tenure security has been strengthened by four other land-related laws (Rao et al. 2016).

In India, the new National Agroforestry Policy was issued in 2014, with the intention of improving land productivity and the livelihood of farmers in remote areas through the equitable recognition of tenure rights and resource sharing (Bose 2015). This step is crucial for many Indian farmers because many provinces, such as Kerala, have no clear policy regarding agroforestry practices prior to 2014. In addition, ex-sectoral land tenure policies encourage many farmers to adopt monocultures, especially in marginal areas (Guillerme et al. 2011).

These results from India illustrate the benefits of agroforestry policy development, now intensively ongoing in many countries and also promoted by international organisations such as the World Agroforestry Centre (ICRAF) and FAO (cf. Buttoud 2013).

Tree rights may be more important to farmers than land rights for various reasons. For instance, land rights are perceived as unnecessary, or, alternatively, farmers are not allowed to own land or they are not willing to obtain land rights (Bruce and Fortmann 1999). In the absence of proper land ownership, tree rights appear to have an important role in sustainable land-use management. In the case of Sudan, acacia trees integrated with crops in rain-fed farming have the potential for improving soil fertility and farm productivity.

Equally important is the fact that trees can provide, for the local people, additional products such as fodder, wood for construction and fuel, and non-wood forest products, of which gum arabic is the most important example in Sudan. However, despite the abovementioned benefits, farmers in Sudan are still hesitant of retaining trees on their farms for long-term benefits, obviously due to land insecurity (study II).

In the literature related to agroforestry practices, farm size also has a conspicuous influence on the adoption of agroforestry. Several studies (Franzel 1999, Mercer 2004, Marenya and Barrett 2007, Muneer 2008) claim that the majority of farmers have relatively small farms; this obviously contributes to their decision to neglect the practice of agroforestry. Under such conditions, farmers might face serious challenges regarding the sustainability of their livelihoods, much because of the absence of trees that would have the ability to recharge soil fertility (IFAD 2007).

Agricultural extension has an important role in disseminating knowledge on the role of agroforestry systems in enhancing land productivity and thus also the livelihoods of people. In the Dhanusha region of Nepal, periodical interactions between farmers and local extensionists lead to increased adoption of agroforestry-based land management practices (Dhakal et al. 2015). In an analogous way, a considerable number of farmers in western Tanzania gave less attention to practicing the improved fallows technology based on legume trees, due to the lack of interaction between them and extension workers (Matata et al. 2010). It seems that interaction between farmers and extension agents is indispensable to increasing the adoption of agroforestry systems among the majority of farmers, especially in vulnerable areas (Lasco et al. 2014). Further factors that also may have a negative impact on the adoption of agroforestry include uncontrolled animal movements on farms, a low educational level of farmers and the lack of supporting materials, such as tree seeds, fuel, and machines for preparing land for growing crops and trees together.

In general, evidence suggests that agroforestry should be given high attention as a promising land-use option for alleviating poverty and improving food security (Luedeling et al. 2016). Exante studies suggest that agroforestry has already been recognized worldwide as an integrated approach toward sustainable land use, ultimately leading to increasing food production and environmental benefits (Nair et al. 2009).

2.3. Factors affecting the variation of crop yields

Rain-fed agriculture, i.e. “dry farming”, is defined as the practice where rather than using irrigation, crops are cultivated under rainfall conditions, which typically corresponds to approximately 500 mm of precipitation per year (FAO 2010). Conceivably, a clear interlinkage between crop production and weather conditions is observed in most cases, especially as related to the inter-annual or inter-seasonal variation in rainfall. Other factors, such as weeds, low soil fertility, land-use changes and lack of access to agricultural input or weather forecast data, might concurrently negatively influence agricultural crop yields.

Rain-fed agriculture is also described as a seasonal activity where crop production is vulnerable to several climatic factors including the variability of rainfall and temperature (Ahmed et al. 2012, Bussmann et al. 2016). Indeed, a lack of knowledge still governs regarding meteorological drivers of crop cultivation. This may lead to an expansion of the gap between the producers and users of climate information. On the other hand, the level of risk perception regarding climate and weather differs largely between producers and users (Jones et al. 2015). For the impacts of a predicted climate change, several studies therefore use scenarios or models to exemplify the potential effects on crop production, specifically in rain-fed agricultural areas (Chen et al. 2013, Evangelista et al. 2013, Grossi et al. 2013, Hadgu et al. 2015, Palazzoli et al. 2015). In addition, other studies attempt to address farmers’ concerns of local effects of climate and weather on crop yields (Belachew and Zuberi 2015, Mapfumo et al. 2015). More specifically, the potential decline in crop yields in many regions of the SSA due to climate change will also be based on localized climate change scenarios (Waha et al. 2013). However, it can be concluded that agricultural crop production is vulnerable to the increased threat of climate change, which in turn will lead to livelihood instability for the vast majority of people in these regions (Ahmed 2010, Bannayan et al. 2011, Funk et al. 2011, Ambrosino et al. 2014, Mbow et al. 2014a, Babikir et al. 2015, Goenster et al. 2015).

Sorghum and pearl millet, the two main staple crops for nearly the entire population living in rain-fed agricultural zones in Sudan, are under the risk of climate change and variability (NAPA 2007). Between 2013 and 2014, sorghum and millet show a substantial variation in yields as a result of local weather conditions (Anon. 2015). In fact, the rainfall pattern trends in many regions of Sudan since the 1960s indicate higher variation in precipitation than the normal reference index (Elagib and Elhag 2011b, Mohamed et al. 2014). Consequently, the country is characterized as one of the most vulnerable nations to climate change on the African continent (Sassi and Cardaci 2013a, Sassi 2013b).

In Africa in general, climatic variations will most likely also affect water resources and shorten the growing season. Such scenarios appear to have serious implications for agricultural systems production in semi-arid and arid zones, with dramatic consequences for food security in this particular continent (Hassan and Nhemachena 2008, De Fraiture et al. 2010). As to be expected, the gap between crop production and food demand is also projected to increase dramatically in many African countries, including Sudan (Haddad et al. 2011).

One of the most serious problems related to land use, particularly in drylands, is soil degradation. Land-use changes, such as conversion of forests to farmland, have a direct impact on ecosystem dynamics, including soil processes, as well as on biodiversity and environmental sustainability as a whole (Sulieman and Elagib 2012, Eltoum et al. 2015). However, most studies on these issues that take place in the drylands of the SSZ focus on addressing the challenge of vegetation cover changes by using remote sensing applications, and fail to examine the true relationships between vegetation and other environmental elements (Karlson and Ostwald 2016).

The negative impact of anthropogenic activities on natural resources, forests in particular, is attributed in most, if not all cases, to a high demand for agricultural lands, natural pasture, and wood for building materials and energy, and to an increasing population (Nassrelddin et al. 2012, Babikir et al. 2015, Lewis et al. 2015, Foli and Abdoulaye 2016). This implies that producing enough food or providing necessary wood materials without jeopardizing sustainability in natural resources management is still challenging, particularly in tropical regions where population growth rates are relatively high (Berhe and Retta 2015). It is well known that the expansion of agricultural farming at the expense of natural forests commonly causes land and environmental degradation and instability in farm productivity (Ahmed and Sanders 1998, Eltayeb and Osman 2011). Problems related to land-use change thus have the potential to increase global food insecurity, with major consequences for hundreds of millions of people and the poor in particular (Mirzabaev et al. 2015).

Sudan's agricultural expansion upon natural forestlands is still incessant (Sulieman and Elagib 2012). During a short period between 2012 and 2013, the cultivation area of sorghum, millet and sesame has increased about 14, 40 and 53%, respectively (CBoS 2013). Even in the SSA in general, the area of sorghum cultivation has also increased by some 72% between 1982 and 2012, with apparent expansion especially experienced in Sudan (former) and Nigeria (FAOSTAT 2013). Thus, Sudan is witnessing extraordinary rates of deforestation as a result of intensified land use, including the production of wood for fuel and construction (Daur et al. 2016). During the period 2000–2010 Sudan ranked third after Tanzania and Venezuela in terms of the world's highest deforestation rates; for this country the annual loss was estimated at 74 000 ha (FAO 2015a).

In Africa, agricultural crops are susceptible to noxious weeds and, specifically, to one group of dangerous parasitic weeds, i.e. the *Striga* species (Kamara et al. 2014). The adoption of monocropping systems that largely prevail in Africa leads to significant negative impacts on soil fertility and subsequently promotes the spread of these weeds (Ibrahim et al. 2015). These parasitic plants have the potential to substantially decrease crop production, as is now the case with sorghum and pearl millet in the SSA (Ardö and Olsson 2003, Bussmann et al. 2016). Agricultural production is precarious under such conditions, and upwards of 400 million farmers living in that particular zone are affected by these weeds as these farmers fundamentally rely on cereal crops to safeguard their annual food securement (Ehui and Pender 2005, Matata et al. 2010, Midega et al. 2015).

Synthetic herbicides or hand tools e.g. machetes have so far been used to control weeds on most African farming lands. Synthetic herbicides reduce weeds on farmlands in versatile ways when properly used, and their application typically requires 88 to 97% less time than manual weeding (Rodenburg et al. 2015). For example, in Nigeria the application of herbicides, such as 2,4-D or atrazine, shows noteworthy impact in reducing weeds on farms compared with manual weeding, resulting in increased maize crop production (Ishaya et al. 2008). However, other methods also show significant results in reducing especially parasitic weeds on farmlands, including delayed sowing, integration of herbicide application with manual weeding, the adoption of intercropping systems, and following of crop rotations (Rubiales and Fernández-Aparicio 2012).

Agricultural inputs, such as herbicides, pesticides and fertilizers, have significant roles in removing weeds and improving farm productivity. Nonetheless, numerous farmers in arid and semi-arid zones of the SSA appear to experience challenges in accessing such important inputs, either due to their costliness or other limitations (Smithson and Giller 2002, Rubiales and Fernández-Aparicio 2012). This situation is aggravated in many cases by only affluent farmers having access to agricultural credits, regardless that poor farmers are majorities (study II). Such credits have the potential to improve farm productivity and socio-economic characteristics in general (Pender and Gebremedhin 2008, Yakubu 2016). Lack of access to formal credits may therefore lead to altered agricultural practices irrespective of meteorological drivers of production (Webber et al. 2014).

On the other hand, a considerable number of farmers appear to also be faced with challenges in accessing weather information, such as rainfall data, which often results in crop failure. Accordingly, many farmers use their local knowledge for determining a suitable sowing day, and this method is currently the best adaptation strategy for mitigating the risk of climate variations and crop failure in general in the SSA (Waha et al. 2013, Bussmann et al. 2016). Consequently, ways for addressing the lack of rainfall data and agricultural credits should be available to improve crop production and secure livelihoods especially in arid and semi-arid zones (Aune and Ousman 2011, Asafu-Adjaye 2014).

3. Material and Methods

3.1. Study area and research sites

The present study was conducted in Sennar state of Sudan, which is one of 18 states in the country, located approximately 360 km southeast of the capital Khartoum, between longitudes 32º 58′ and 35º 42′E and latitudes 12º 5′ and 14º 7′N (Fig. 3). The total area of Sennar state is approximately 40 680 km^2 (Ahmed et al. 2015). It is generally flat, rich in natural resources and diverse in agricultural patterns. Rain-fed farming covers virtually 90% of the agricultural land use, while irrigated schemes are found on only 10% of the total farming land. In general, agriculture is considered the main economic activity in the state, as the majority of people depend on it for securing their livelihoods (Sam and Elmahadi 2008).

The state consists of seven localities: Sennar, East Sennar, Singa, El Suki, El Dali and El Mazmum, El Dinder and Abu Hojar. These localities are divided into twenty-one administrative units. The total population of Sennar state is estimated at ca. 1 400 000 persons, more than 75% of whom live in rural areas (CBS 2012). The state is considered one of the main livestock production areas, with the total number of livestock including cattle, sheep, goats and camels estimated at approximately 9 000 000 heads (Abusuwar and Abdelaziz 2010).

The study area is characterized by semi-arid environments; the rainy season is confined more or less to between June and October. In November, a transition period occurs towards the winter dry season that ends in February, while the summer's dry months span from March to May, when the daily temperature is usually above 30º C and relative humidity more than 20% (Sennar meteorological data 2011 unpublished).

During 1960–2000, the mean annual precipitation in Sennar state was 445 mm $year^{-1}$, which has decreased to ca. 424 mm $year^{-1}$ (-21 mm) between 2000 and 2010 (Mohamed et al. 2014).Tree species able to cope in such conditions in this particular zone include short thorny trees e.g. *Acacia mellifera* (known locally as kitir), *A. seyal* (talh), *A. senegal* (hashab) and *Balanites aegyptiaca* (heglig). Together, natural forests and rangelands occupy more than 12% of the total land area of the state (IFAD 2010). Soils in Sennar state predominantly consist of dark alkaline clay. It is sticky when wet, but develops wide and deep cracks once dry due to the high content of the expansive clay mineral montmorillonite (Ahmed et al. 2012).

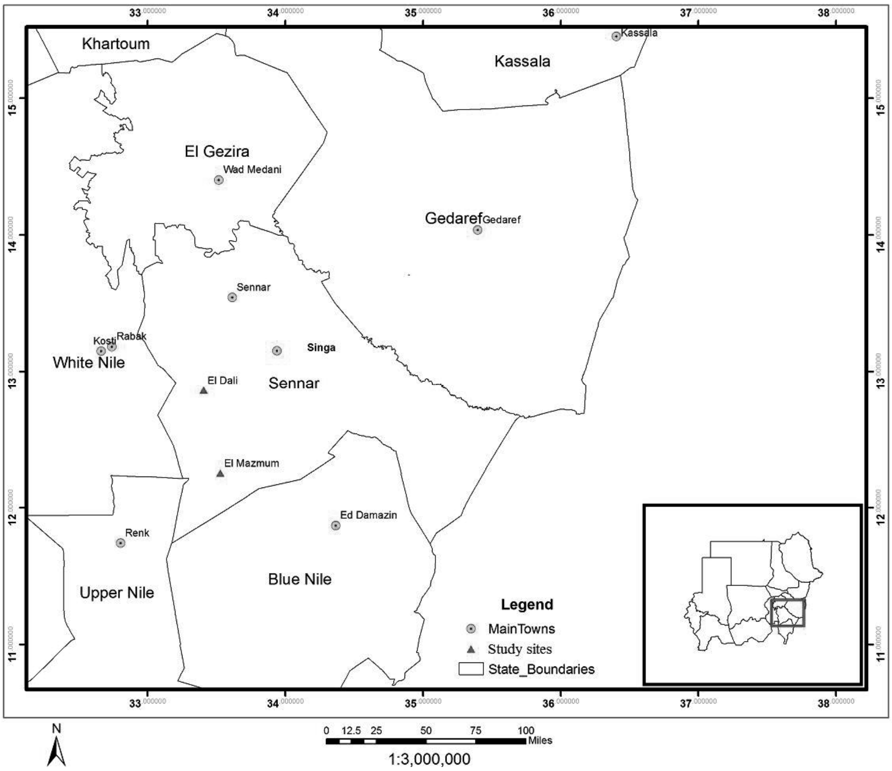

Fig. 3 Map of research sites (El Dali and El Mazmum) in the study area of Sennar state, Sudan

El Dali and El Mazmum, the two separate administrative units that together form the El Dali and El Mazmum locality, were selected as the research sites (Fig. 3). An important reason for choosing these particular sites was a previous history of socio-economic research conducted in this area and possibility to add new findings to earlier results on factors affecting land-use here (cf. Younis 1995, Luukkanen et al. 2006, Adam et al. 2015).

El Dali and El Mazmum research sites lie in the southwest corner of Sennar state, reaching the border of the Upper Nile state in South Sudan (Fig. 3). Both of these sites show an expansion of both government-supported rain-fed mechanized agricultural schemes and rain-fed subsistence farming which together occupy an area of approximately 917 000 ha (cf. Annex 3). The main cultivated crops include the main food crop sorghum (locally known as *dura*), the main cash crop sesame (*simsim*), and pearl millet (*dokhon*), which is considered both a food and a cash crop.

Tree species, such as *A. mellifera* and *A. senegal*, sparsely occupy ca. 10% of the area within agricultural schemes at both sites. Moreover, forests known as state forests and gum arabic schemes are administered by the Forests National Corporation (FNC); their total area in Sennar state is ca. 68 000 ha. The central goal of these forests and gum arabic schemes is to produce firewood, charcoal and gum arabic, and to increase the income of local people through participatory forest management. However, the area of these forests has been reduced over time due to the expansion of rain-fed agricultural farming. To give an example, the tree cover at El Gewezat and Al Gabia Al Reqeta forests in the El Dali area is less than 10%, consisting mainly of scattered *A. mellifera* trees, although the total area of these forests are 2656 and 13 937 ha, respectively (FNC 2015).

According to the latest figures recorded by the rangeland sector in Sennar state, the total livestock (sheep, goats, cattle and camels) in the El Dali and El Mazmum locality was estimated at approximately 716 000 heads in 2011. However, it increased to 6 716 000 heads later during the same year, after the abovementioned livestock estimation was carried out, as numerous pastoralists and nomads decided to settle in the area when South Sudan was separated from Sudan in July 2011. They had thus moved approximately 6 000 000 heads from South Sudan and settled in the El Dali and El Mazmum locality (RSSS 2011).

The mean annual rainfall at the two study sites between 2001 and 2015 varied from 300 to 800 mm year^{-1}, thus indicating large variation between years (Fig. 4). According to 2001–2015 rainfall data from the locality, the wet season normally occurs between May and October, while an occasional shower with less than 50 mm of rainfall may occur during April. Concurrently, several agricultural operations take place during the rainy season. Initially, land preparation is normally conducted between May and June using hand tools or tractors. Subsequently, farmers sow their cereal crops manually in pits or using machines during June and July, relying on their indigenous knowledge for estimating the time of the onset of rains. Some farmers apply a herbicide (2,4-dichlorophenoxyacetic acid) to remove weeds, while others, typically smallholders, merely use machetes along with hoes to eradicate them. Farmers harvest their crops either using hand tools or with harvesting machines, after which the crops are cleaned and finally packaged in sacks.

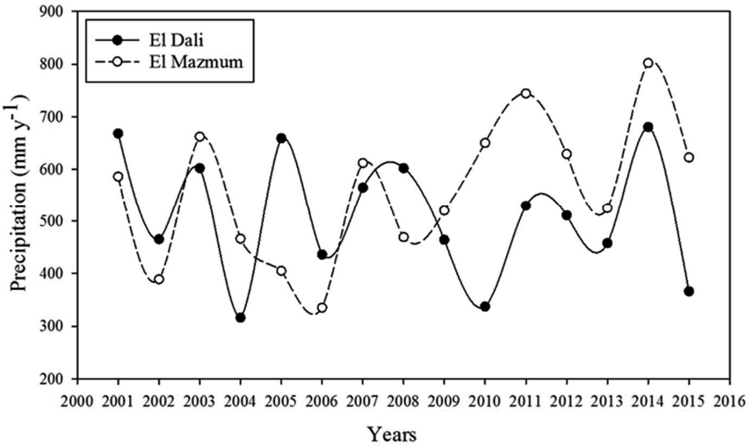

Fig. 4 Average annual precipitation (mm y^{-1}) at El Dali and El Mazmum study sites in Sennar state, Sudan, between 2001 and 2015.

3.1. Data collection and analysis

At the beginning, the study was carried out as a preliminary survey with the goal of visiting approximately twenty villages in El Dali and El Mazmum locality. The same survey aimed to obtain consent from village leaders to collect data for the present study and to scrutinize the research questions so as to render them understandable to all respondents. The data gathered during the preliminary survey were used together with information obtained from the village leaders to classify the villages at the El Dali and El Mazmum locality into three categories: large, medium or small, based on the number of households in each village. A random sampling method was next used to select nine villages for the case studies. The same procedure was used to hand pick a total of 281 households (145 from El Dali and 136 from El Mazmum). The heads of each household were interviewed face-to-face using a pre-structured household questionnaire (more details in study II). The main data used in this dissertation were collected between July and November 2011, and the supplementary data required after the preliminary analysis were later acquired between September and November 2012.

Five types of data were collected as follows:

(1) Data on households and their socio-economic aspects were obtained from 281 households using a pre-structured questionnaire written in Arabic and translated into English. Some information was gathered during informal discussions and interviews with key informants.
(2) Data on crop yields during 2001–2010 were provided by the 281 selected households from their annual estimate records. The study was aimed to also incorporate additional information such as agricultural inputs e.g. herbicide usage, farmer's perceptions on the impact of rainfall variability and possible climate change impacts on crop yields.
(3) Field observations were carried out to better understand techniques utilized during land preparation, sowing, the control of insects, weeds and birds, and the harvesting of crops.
(4) Rainfall data: Mean monthly precipitation data for El Dali and El Mazmum for the period between the period 2001 and 2010 were acquired from the Ministry of Agriculture, Animal Wealth and Irrigation (MAAWI), Sennar state, Sudan (Annex 2). Additional rainfall data for 2011-2015 were later received in 2015 and used only in the summary of this dissertation, and
(5) Maps of land-use and land-cover changes for the El Dali and El Mazmum areas during the period between 1972 and 2010 were obtained from the RSA.

The results of a preliminary analysis used to screen the collected household data showed incomplete information for some households that were later excluded; consequently, studies I, II & III are based on complete information from 274, 270 and 275 households, respectively.

Quantitative and qualitative analyses, such as descriptive statistics, multiple regression analysis, logistic regression and one-way analysis of variance (ANOVA), were used in studies I, II & III to analyse the collected data of the households, farming systems and other agricultural operations associated with crop yields using the Statistical Package for the Social Science (SPSS v. 19), (IBM SPSS statistics v. 22) and (SigmaPlot v.11 and 13) programmes.

In study I, an economic analysis was used to obtain the financial return of sorghum, millet and sesame yields for various land-use systems and treatments e.g. herbicides. A net present value (NPV), and benefit/cost ratio (B/C ratio) based on profitability criteria were applied using a 12% annual discounting rate, because it reflects the mean alternative rate of return to financial private investment throughout the country during 2001–2010. Costs and income data of each land-use system acquired from respondents were analysed using Equations 1 and 2:

$$NPV_i = \sum_{n=0}^{N} \left(B_n - C_n\right) * \frac{1}{(1+i)^n} \tag{1}$$

$$B/C\ ratio = \frac{\sum_{n=0}^{N} B_n * \frac{1}{(1+i)^n}}{\sum_{n=0}^{N} C_n * \frac{1}{(1+i)^n}} \quad (2)$$

where Bn, Cn equal the annual benefit and cost, i the discounting rate, and n the number of years.

In studies I & III, ANOVA and the independent-sample t-test were used to compare the variation in average crop yields of sorghum, millet and sesame (2001–2010) cultivated in various land-use systems and treatments between the two study sites. Additionally, one sample T-test, at $P \leq 0.05$ significance level, was used to determine the variation during 2001-2010 in average crop yields of the three crops, which were cultivated in various land-use systems, but separately within each of the two study sites. Several graphs were created using the SigmaPlot programme (v.13) with results from the independent-sample t-test.

Logistic regression analysis has extensively been used in agroforestry studies (Salam et al. 2000, Otsuka et al. 2001, Nkamleu and Manyong 2005). It is considered a suitable method as it allows the use of data comprised of dichotomous dependent variables for testing models and to predict distinct outcomes from a set of explanatory variables. These variables can either be continuous, categorical, or a medley in one model (Pallant 2007, Tabachnick and Fidel 2007). In this study, logistic regression was used to identify the determinants of agroforestry interventions from the viewpoint of both farmer types, either tree-retaining or treeless farmers at the two study sites. The test used in this study is known as the Wald test, where the value of a statistic for each predictor in the column is labelled Wald. Variables that contributed significantly to the predictive ability of the model to test determinants should have a statistic for significance of less than 0.05.

To run the logistic regression model, tree-retaining farmers forming agroforestry systems and treeless farmers were characterized by a population sample, which is specified as:

$$\ln[P_i/(1-P_i)] = \beta_0 + \beta_1\chi_{1i} + \beta_2\chi_{2i} + \beta_3\chi_{3i} + \cdots + \beta_k\chi_{ki} \quad (3)$$

where subscript i denotes the i-th observation in the sample, P is the probability of the outcome given as a set of explanatory variables, β0 is the intercept term, and β_1, β_2, β_3, and so on, are called regression coefficients associated with each explanatory variable X_1, X_2, X_3 respectively.

In study II, the dependent variables were tree-retaining farmers, who intentionally kept trees on their farmland to form agroforestry parklands systems, and treeless farmers, who were not enthusiastic of sustaining trees on their farmland. The dependent variables were defined as a binary variable with a value of 1 given for tree-retaining farmers and 0 for treeless farmers. Initially, nine explanatory variables were identified and introduced into the model. However, after several processes for checking the data to correct the assumption of violations and excluding redundant variables to address multicollinearity, only five self-explanatory variables, namely (1) incentive received from the government, (2) incentive received from agricultural union, (3) administrative unit, (4) household size and (5) land size were used in the subsequent analysis. The dichotomous explanatory variables were formed for 1, 2 and 3; a value of 1 was assigned to those who received incentives and farmers from the El Mazmum administrative unit, and a value of 0 to those that received incentives and for farmers from the El Dali administrative unit, respectively.

The corresponding dummy variables were also used because household and land size were distributed into several categories: less than 8, between 8 to 15, and greater than 15 persons, and less than 42 ha, 42 to 166 ha, 166 to 420 ha, and >420 ha, in that order. For examining each category variable, e.g. households with less than eight persons, respondents belonging to this category were given a value of 1, while a 0 value was assigned to respondents not belonging to this category. A similar method was applied for all other category variables. The logistic regression model was analysed using SPSS v.19, while results were explained in terms of the odds ratio.

In study II, cross tabulation analysis was also used to examine farmer's perceptions concerning constraints hindering the spread of agroforestry practices at both the El Dali and El Mazmum sites. The study suggested that a lack of extension services, planting materials, tree tenure problems, overstocking of livestock and small land sizes constrained the prevalence of agroforestry practices and were therefore examined from the viewpoint of both tree-retaining and treeless farmers at the two study sites.

The Excel template MAKESENS (Mann-Kendall test for trend and Sen's slope estimates) has been broadly used to detect trends in hydro-meteorological time series data (Salmi et al. 2002, Partal and Kahya 2006). In study III, the same method was used to detect and estimate trends in the time series of annual precipitation (mm year^{-1}) and crop yield (kg ha^{-1}year^{-1}) between 2001 and 2010, and possible relations between them. The procedure is based on the non-parametric Mann-Kendall test for detecting a monotonic trend in the time series of a dataset, and Sen's non-parametric method is used for detecting the magnitude of the trend as measured by a linear model for estimating the slope of the trend (Mann 1945, Kendall 1975). Nevertheless, the variance of the residuals should be constant in time.

MAKESENS software provides two forms of statistical analyses: (1) testing of a monotonic, increasing or decreasing trend in a data set using the non-parametric Mann-Kedall test, and (2) Sen's non-parametric method for estimating and computing the slope of a linear trend (Gilbert 1987). The tested significance levels α in this programme are 0.001, 0.01, 0.05 and 0.1. However, n should be greater than 7 for significance level α at 0.001.

In study IV, the satellite images of land-use/land-cover changes (LULC) for El Dali and El Mazmum between 1972 and 2010 were provided by the RSA. A geographic information system (GIS) was used for analysing the collected georeferenced data. Four subsets of images (1972, 1987, 1999 and 2005) were geometrically and radiometrically corrected. Subsequently, cloud-free Landsat Multrispectral Scanner (MSS) (resolution 60/m, band 6, path 174 and row 51), Thematic Mapper (TM) and Enhanced Thematic Mapper Plus (ETM+) (resolution 30/m, band 6, path 174 and row 51) scenes were covered at the two study sites. These four images were used for the visible, near- and mid-infrared regions of the electromagnetic spectrum. Various software including ERADS IMAGINER 8.5, Arc GIS 9.3, Definiens eCognitionVersion 8, and GLCN MadCat_2009_03_25_v3.1 were used to create land-use images. The Mapping Device–Change Analysis Tool (MAD-CAT) combined with the Land Cover Classification System (LCCS 2.4.5) (Dec 2004) was used for data processing and classification, in which the present study mainly focused on two classes, (1) forestland, and (2) rain-fed agricultural land.

Additionally, the Africover project 2010 (FAO/ Sudan) allowed the use of the FAO Land Cover Classification System (FAO LCCS) as ancillary supporting data with SPOT4 satellite imageries (resolution 20 m). GLCN MAD-CAT and LCCS were used for classifying and labelling, and transferred the data into shape file format for completion, dissolving and layout processing in ArcGIS 9.3.

4. Results

4.1. Household data (studies I, II & III)

Figure 5 (a–f) shows agriculture to be a favoured activity of entire households at both study sites. Management of a family farm is either the responsibility of the household head, often exceeding the age of fifty, or one of his sons, usually less than forty years of age. Substantial differences in educational level were observed between household heads. The most common family size at the research sites was eight to 15 persons. Crop production was considered a decisive source of income, but some households rely on animals and crop as a joint source of income.

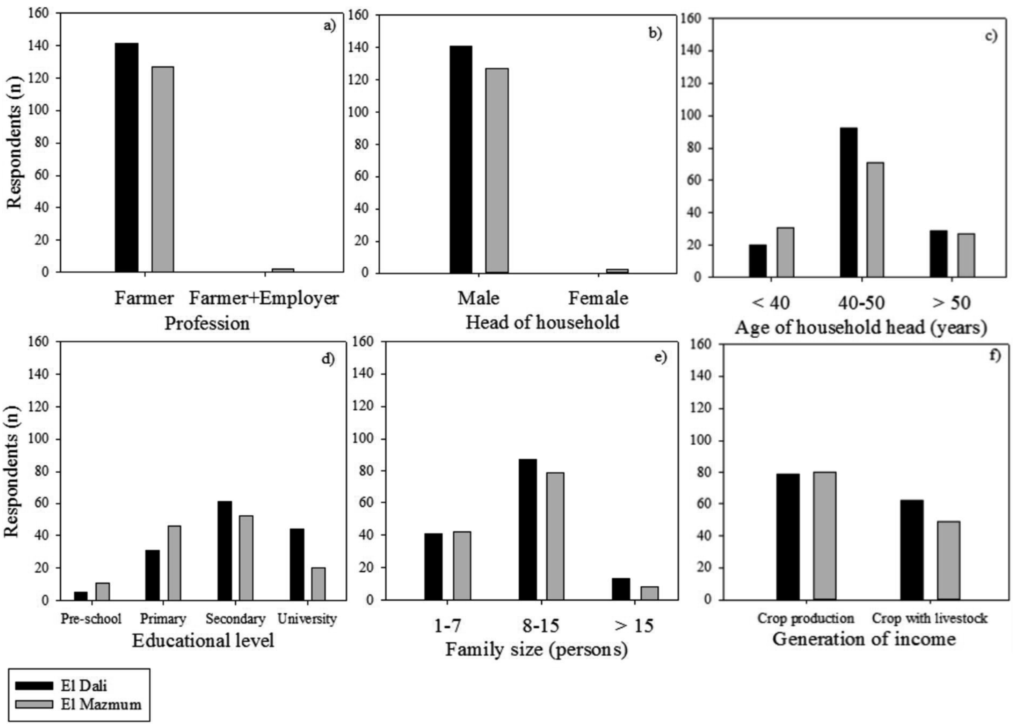

Fig. 5 (a–f). General characteristics of households in the El Dali and El Mazmum study sites in Sennar state, Sudan.

Farming systems and other factors related to crop yield are shown in Figure 6 (a–f). Most households at both sites had adopted monoculture systems to grow their food and cash crops, but a small number of households had continued practicing agroforestry parkland systems. Average farm size at the two study sites was approximately 42 hectares for the majority of households, both leaseholders and landless ones. Contrastingly, some households at the same two sites owned large holdings exceeding 420 hectares in size. Small-scale households mainly used hand tools when preparing their land, removing weeds and harvesting crops. In contrast, large-scale households used machinery to execute such operations; they additionally also used herbicides to exterminate weeds. Sorghum, millet and sesame were the paramount crops cultivated on farmland at the two study sites, with farmers aiming both for food security and income generation.

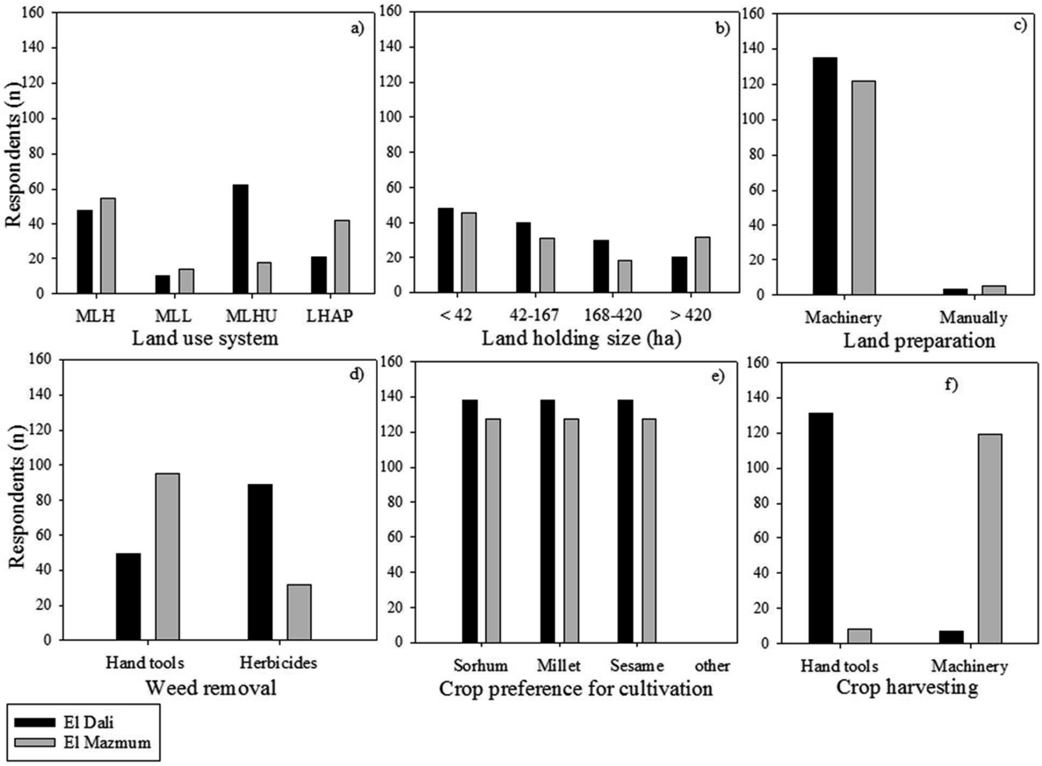

Fig. 6 (a–f). Land-use systems and other factors related to crop yields at the El Dali and El Mazmum study sites in Sennar state, Sudan.

Note: MLH; monoculture by leaseholders, MLL; monoculture by landless farmers, MLHU; monoculture by leaseholders with herbicide use, and LHAP; leaseholders in agroforestry parklands.

The main constraints underlying farm productivity improvements in El Dali and El Mazmum are presented in Figure 7 (a–f). A majority of households at both sites owned land, but under the customary law known as "leaseholder farmers". Those without such arrangements annually hired land from leaseholders to cultivate their crops. All farmland turned out to officially belong to the government, and households could lease it upon a formal ten-year contract that could be renewed after the end of the period. The lack of permanent title seemed to be the main reason discouraging farmers from integrating trees with crops to create long-term agroforestry parkland systems. This despite households that had abandoned to practice agroforestry parkland claimed it to be the best land-use system in terms of crop yields and income generation. Additional constraints included a lack of agricultural inputs e.g. herbicides and fertilizers, a lack of loans from the Agricultural Bank especially to small-scale farmers, inter-annual rainfall variation and weeds on farmland.

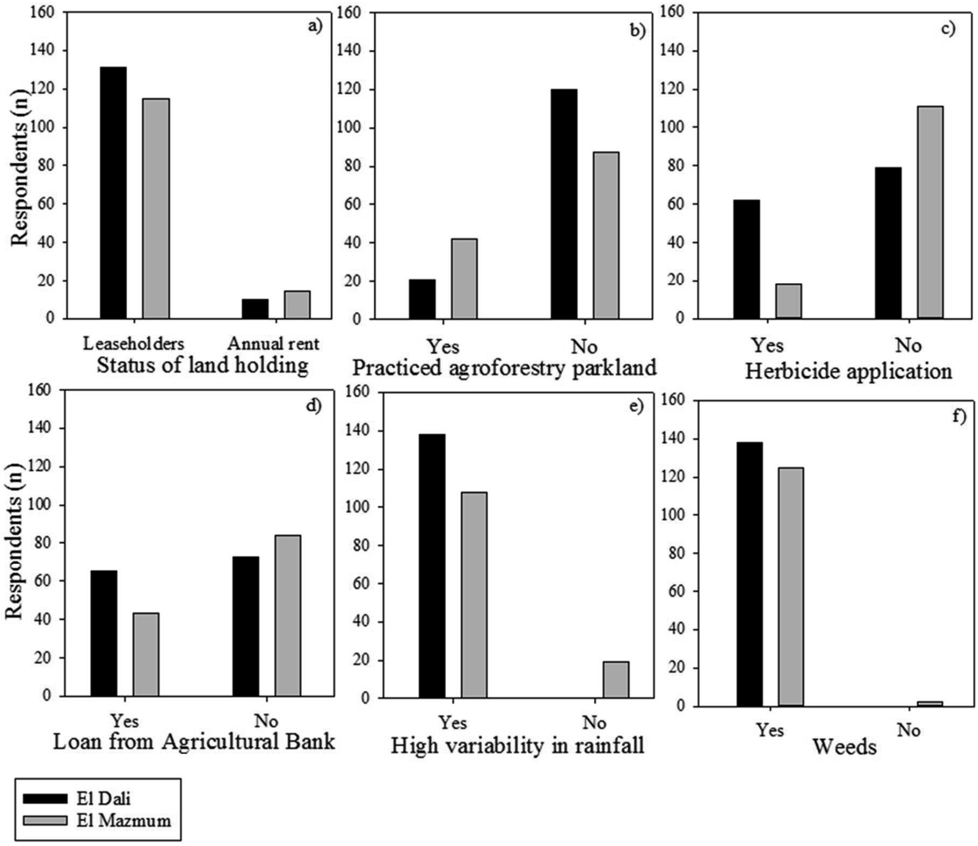

Fig. 7 (a–f). Constraints related to crop yields at the El Dali and El Mazmum study sites in Sennar state, Sudan.

4.2. Crop profitability with various land-use systems (study I)

Table 1 shows NPV and the B/C ratio for sorghum, millet and sesame cultivation grown in four different farming systems. It can be concluded that all three crops favoured by farmers were profitable regardless of the land-use system in place[1]. However, of all the land-use systems, the agroforestry parkland system (LHAP) provided the highest net discounted returns steadily throughout. The only contrary case was a sesame crop in a monoculture with herbicide use (MLHU) at El Mazmum, which indicated a slightly higher return compared with the same crop in the LHAP. Cultivation of sesame was also less affected by the land-use system than sorghum and pearl millet. The B/C ratio for sesame remained at a reasonably high level, varying between 1.88 and 2.35 for all farming systems at both study sites, but varying between 1.00 and 1.69 for sorghum and 1.08 to 2.77 for pearl millet.

[1] In Table 6 (study 1), weeding refers to cost of removal of detrimental weeds by manual labour. Similarly, manual harvesting refers to labour cost for harvesting.

Table 1. Financial return (USD$ ha^{-1}) of sorghum, millet and sesame grown in four different land-use systems at the El Dali and El Mazmum study sites in Sennar state, Sudan.

Crop	Indicators of land-use performance	El Dali				El Mazmum			
		MLH	MLL	MLHU	LHAP	MLH	MLL	MLHU	LHAP
Sorghum	Total discounted costs	319.7	389.5	354.9	362.4	290.9	370.4	367.8	389.8
	Total discounted benefits	362.9	442.2	418.4	544.3	303.9	371.7	473.0	657.5
	$NPV_{12\%}$	**43.2**	**52.8**	**63.5**	**181.9**	**13.3**	**1.3**	**105.2**	**267.8**
	B/C $ratio_{12\%}$	**1.12**	**1.14**	**1.19**	**1.50**	**1.04**	**1.00**	**1.29**	**1.69**
Millet	Total discounted costs	291.7	376.3	344.9	340.7	300	358.9	330.4	308.8
	Total discounted benefits	315.5	541.8	489.8	604.5	356.6	430.4	411.2	411.5
	$NPV_{12\%}$	**23.7**	**165.5**	**144.9**	**263.8**	**56.6**	**71.5**	**80.8**	**102.6**
	B/C $ratio_{12\%}$	**1.08**	**1.44**	**1.42**	**2.77**	**1.19**	**1.20**	**1.24**	**1.33**
Sesame	Total discounted costs	586.9	607.8	624.1	673.5	557.4	637.0	649.3	622.3
	Total discounted benefits	1263.5	1141.9	1279.9	1580.2	1079.0	1281.7	1467.2	1434.9
	$NPV_{12\%}$	**676.6**	**534.1**	**655.8**	**906.7**	**521.6**	**644.7**	**817.9**	**812.6**
	B/C $ratio_{12\%}$	**2.15**	**1.88**	**2.05**	**2.35**	**1.94**	**2.01**	**2.31**	**2.31**

MLH= monoculture by leaseholders, MLL= monoculture by landless farmers, MLHU= monoculture by leaseholders incorporating herbicide use and LHAP= leaseholders in agroforestry parklands

4.3. Factors determining the adoption of agroforestry systems (study II)

A logistic regression model containing five independent variables (incentive received from government, incentive received from agricultural union, administrative unit, household size and land size) shows that 82.1% of the determinants were statistically significant X2 (8, N= 274) = 54.229, P < 0.001, indicating that the model rejects the null hypothesis that all logic coefficients are equal to zero in the population. Table 2 shows that four independent variables (household size, the location effect, the incentive received from agricultural unions, and land size) were the main determinants positively affecting farmers to integrate trees with crops on their farmland, while incentives received from the government had a negative impact.

Table 2. A logistic regression model of the determinants for integrating trees with agricultural crops on farmland at the El Dali and El Mazmum study sites in Sennar state, Sudan.

Variables	*B*	S.E	Wald	*Df*	*P*	Odds Ratio	95% C.I. for Odds Ratio	
							Lower	Upper
Household number			5.746	2	0.057			
8–15	1.370	0.589	5.405	1	**0.020**	**3.934**	1.240	12.482
>15	1.115	0.522	4.550	1	**0.033**	**3.048**	1.095	8.487
Location effect	0.988	0.368	7.201	1	**0.007**	**2.686**	1.305	5.529
Incentive from government	-0.773	0.418	3.425	1	0.064	0.462	0.204	1.047
Incentive from agricultural union	0.839	0.385	4.755	1	**0.029**	**2.314**	1.089	4.920
Land size			16.289	3	**0.001**			
42–167 ha	2.295	0.606	14.335	1	**0.000**	**9.927**	3.025	32.569
168–416 ha	0.274	0.424	0.418	1	0.518	**1.315**	0.573	3.021
> 416 ha	0.007	0.452	0.000	1	0.988	**1.007**	0.415	2.439
Constant	-1.224	0.617	3.935	1	**0.047**	0.294		

Reference categories have been omitted from the table.
Bolded values indicate significant contribution ($P \leq 0.05$) to the model prediction.

Interviews and field observation confirmed that the most important patterns for integrating trees with crops on parklands at the two study sites were scattered trees, strips, hedges and shelterbelts. However, scattered natural trees were the most widespread form of agroforestry parkland, despite the study observing that only ca. 20% of all households practiced such a system. The strongest disincentive factors restricting the practice of agroforestry from the viewpoint of both tree-retaining and treeless farmers include the lack of extension services, lack of materials and tools used to plant trees, tree tenure problems, uncontrollable animal movements on the farmland, small farm sizes, the high instability of gum arabic prices and short-term land renting for cropping instead of tree planting (cf. Fig. 8). However, treeless and tree-retaining farmers showed understandably different patterns regarding disincentives for practicing agroforestry.

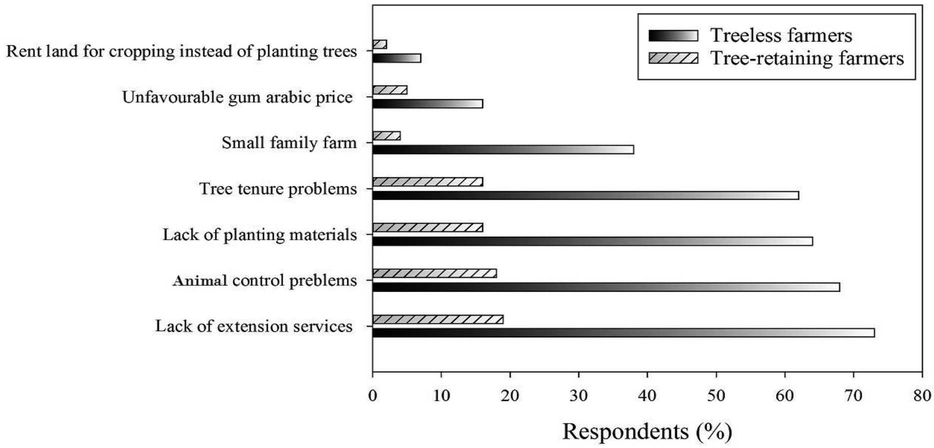

Fig. 8 Farmer's perceptions of constraints when practicing an agroforestry parkland system at the El Dali and El Mazmum study sites in Sennar state, Sudan.

Note: Percentages were calculated separately according to the number of households of tree-retaining (n = 63) and treeless farmers (n = 207).

4.4. Variation in crop yields 2001–2010 (studies I & III)

Figure 9 shows the variability of sorghum, sesame and millet yields during the period 2001–2010. Sorghum yields in El Dali and El Mazmum in 2001 amounted to approximately 970 and 810 kg ha^{-1}, respectively. Nine years later, in 2010, the same crop produced ca. 630 kg ha^{-1} in El Dali and 530 kg ha^{-1} in El Mazmum. However, the millet harvest in El Dali in 2010 was approximately 400 kg ha^{-1}, which is slightly higher than the 340 kg ha^{-1} harvested in 2001. Between 2001 and 2010, the highest sorghum yield (over 1000 kg ha^{-1}) was collected in 2005 from El Dali, while sesame gave the highest yield (630 kg ha^{-1}) in 2003 in the same area, and the best millet yield (600 kg ha^{-1}) was obtained from El Mazmum in 2001.

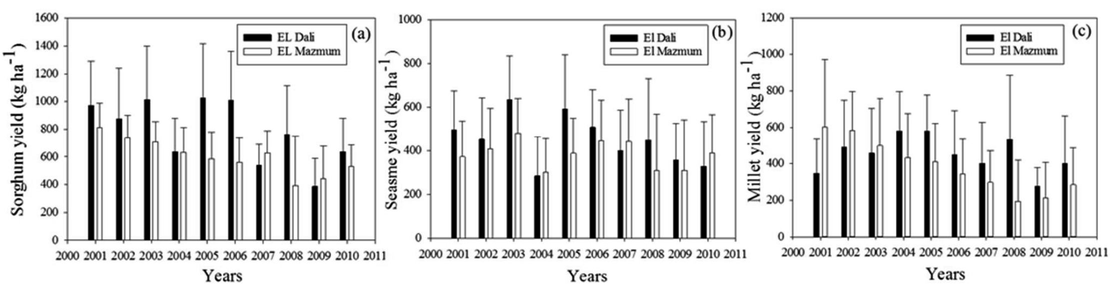

Fig. 9 Mean ± SD of sorghum (a), sesame (b) and millet (c) yields (kg ha^{-1}) from 2001 to 2010 at the El Dali and El Mazmum study sites in Sennar state, Sudan.

4.5. Precipitation and yield trends (study III)

Relationships between the average sorghum, sesame and millet yields (kg ha^{-1}) and annual precipitation (mm y^{-1}) between 2001 and 2010 are shown in Figure 10. The Mann-Kendall test revealed no evident trends in annual precipitation at either study site (Fig. 11). This was further confirmed by the statistical tests at the 95% and 99% confidence levels. Both showed non-significant results at El Dali and El Mazmum (see Table 5 in study III). In contrast, millet and sorghum yields in El Mazmum showed significant declining trends at the 95% and 99% confidence levels during the same period (Table 5 in study III, Fig. 11 here).

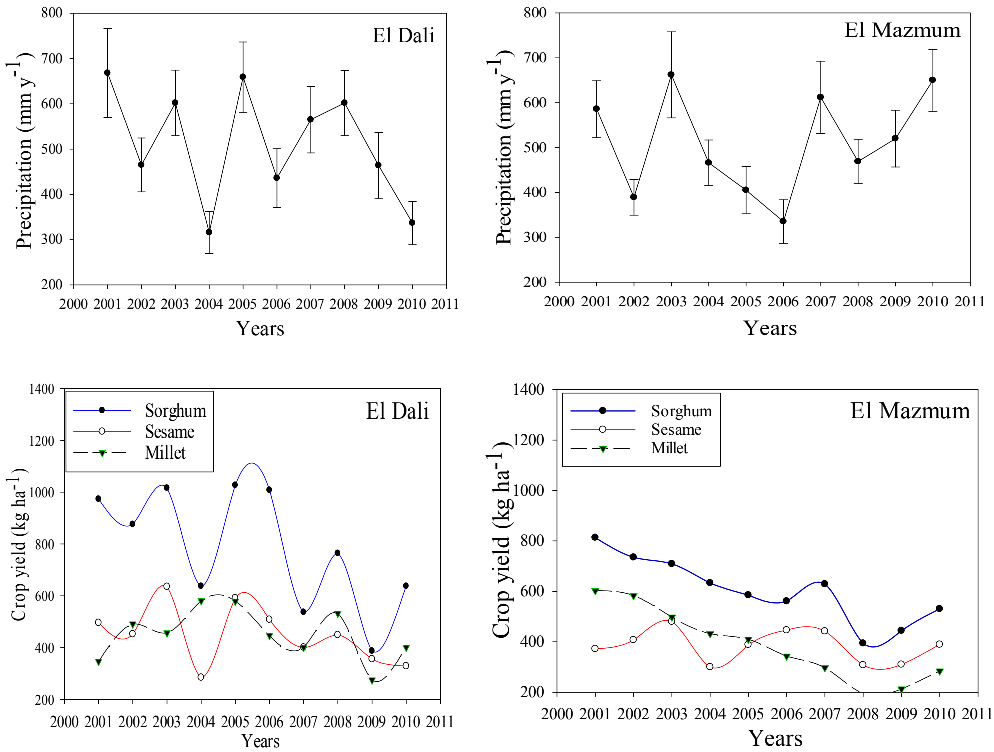

Fig. 10 Relationships between annual precipitation (mm y^{-1}) and crop yields (kg ha^{-1}) between 2001 and 2010 at the El Dali and El Mazmum study sites in Sennar state, Sudan.

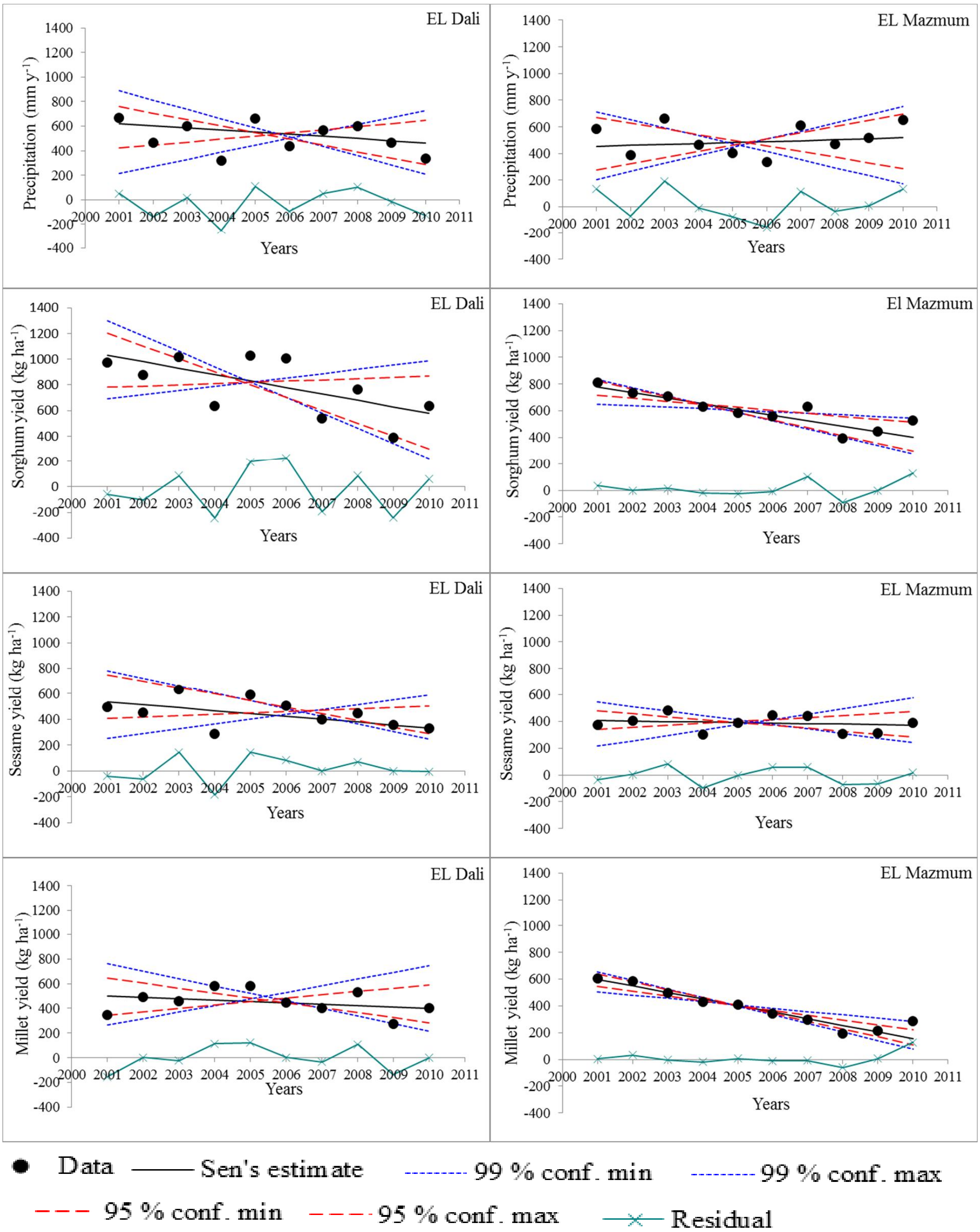

Fig. 11 Trend analysis of annual precipitation (mm y^{-1}) and crop yield (kg ha^{-1}) 2001–2010 at the El Dali and El Mazmum study sites in Sennar state, Sudan, using the Mann-Kendall test and Sen's slope estimates.

4.6. Land-use and land-cover changes 1972–2010 (study IV)

According to satellite images, the study area has experienced unprecedented changes in land use and vegetation cover since 1972 (Fig. 12 a, b). However, post-2005, no clear changes had occurred in vegetation cover, although the forest area showed slight increases in the middle part of the study area as a result from the afforestation of degraded forestland by acacia trees. In contrast, the large-scale clearing of trees seen in the southeastern part of the study area negatively affected forestlands during the same period. By 2010, agricultural farming systems had expanded in almost all areas classified as forestland before 1972.

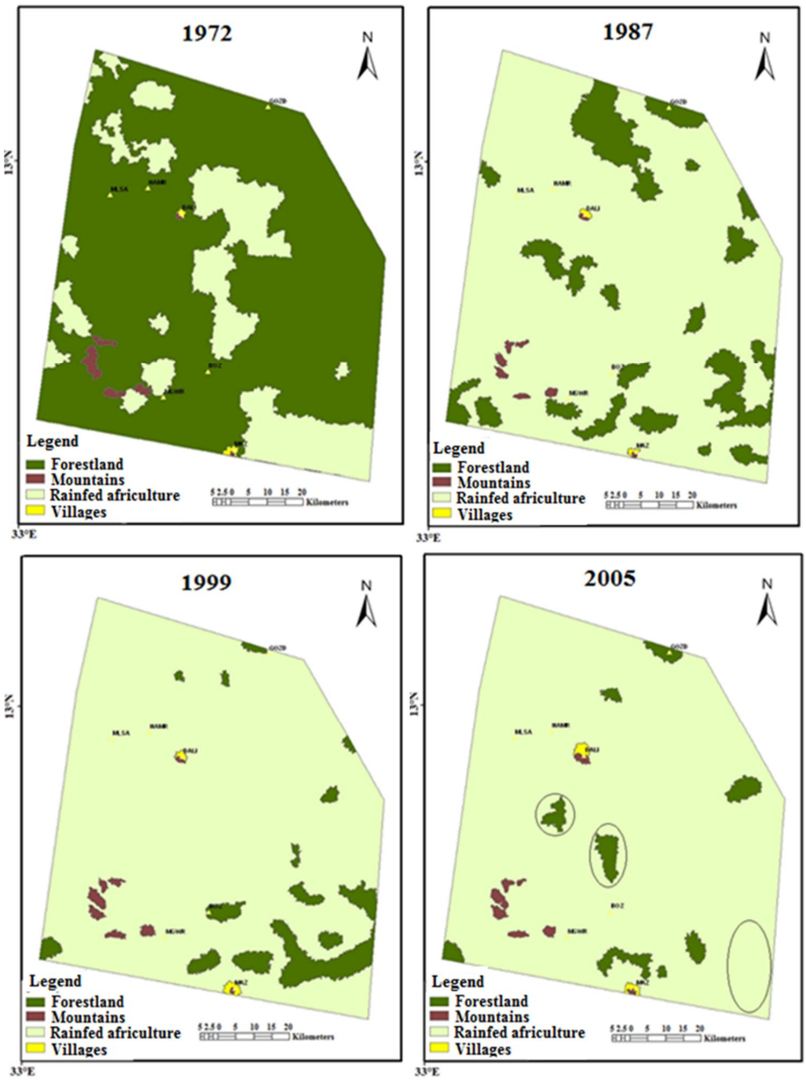

Fig. 12 (a)

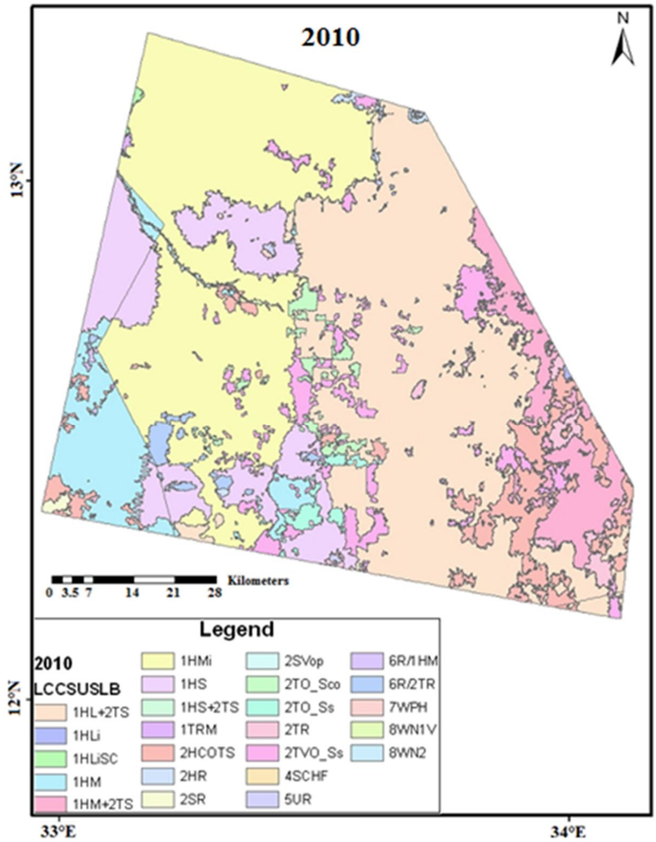

Fig. 12 (b)

Fig. 12 (a and b) Land-use/land-cover (LULC) changes as observed in 1972, 1987, 1999, 2005 and 2010 at the El Dali-El Mazmum study sites in Sennar state, Sudan.

Note: the scale in maps 1972, 1987, 1999 and 2005 explained only the area of forestland and rain-fed agriculture, not village areas.

Legend in map 2010: 1HL+2TS, Rain-fed herbaceous crop(s) + Sparse trees; 1HLi, Permanently cropped area with surface-irrigated herbaceous crop(s); 1HLiSC, Permanently cropped area with surface-irrigated herbaceous crop(s), intercropped (Second Crop); 1HM, Rain-fed herbaceous crop(s); 1HM+2TS, Rain-fed herbaceous crop(s) + Sparse trees; 1HMi, Permanently cropped area with surface-irrigated herbaceous crop(s); 1HS, Small-sized field(s) of rain-fed herbaceous crop(s); 1HS+2TS, Small-sized field(s) of rain-fed herbaceous crop(s) + Sparse trees; 1TRM, Irrigated tree crop(s); 2HCOTS, Closed to open herbaceous vegetation with trees and shrubs; 2HR, Sparse herbaceous vegetation; 2SR, Sparse shrubs; 2SVop, Open (40– (20–10)%) shrubs (Shrubland); 2TO_Sco, (70–60) –40%) Woodland with shrubs; 1TR, Sparse shrubs; 2TVO_Sc, Broadleaved deciduous (40– (20–10)%) woodland with herbaceous layer and sparse shrubs; 4SCHF, Closed to open (100–40%) shrubs with herbaceous vegetation on temporarily flooded land; 5UR, Urban area(s); 6R_2TR, Very stony bare soil and/or other unconsolidated material(s); 7WPH, Artificial perennial water bodies (standing); 8WNIV, Non-perennial natural water bodies (surface aspect: Sand); 8WN2, Non-perennial natural water bodies (flowing) (surface aspect: bare soil).

5. Discussion

5.1. Socio-economic household characteristics (study I, II & III)

Socio-economic characteristics have a fundamental role in determining the status of food security and household's income (Ajani et al. 2006, Babatunde et al. 2007). It has been claimed that the general household characteristics of farming communities who live in the same region do not differ much from each other, mainly because agriculture remains the backbone of the rural economy and of the primary means of households for securing their livelihoods (Kalonga and Kulindwa 2017). In the present study, the vast majority of the rural households, studied in the semi-arid region of Sudan, occupied farms less than 42 hectares in size; this can be compared to the average family size which varied between 8 and 15 persons. Female-headed households were found to be very rare, as is the case in rural areas in Sudan in general (Abdalla et al. 2014, Adam et al. 2015)

However, the socio-economic situations of households of identical sizes may also vary considerably. For many African farmers, the most important household characteristics influencing the type of farming system used, and thus also affecting the status of food security, are farm size and family size (Pender and Gebremedhin 2008). Both factors may encourage the practice of monoculture. Monoculture can be defined as cultivating a sole crop continuously on the same piece of land. In most cases on agricultural lands in Africa including Sudan, this is conducted without such agricultural inputs as herbicides, pesticides or fertilizers. This is especially the case with small-scale farmers, because their budgets often cannot meet the costs involved.

In the entire Sudano-Sahelian region of Africa, sorghum, pearl millet and sesame are prominent crops cultivated under rainfall conditions and favored by the majority of farmers. In specific cases, like those prevailing in the semi-arid rural areas of Sudan, farming households can choose between cultivating these crucial crops either on their own holdings or on land leased annually from another community member. Food security and income generation are the ultimate aims guiding farmers' decisions (de Rouw 2004, Elbashir and Ali 2014, Beshir et al. 2015).

As a result of several factors and constraints, adoption of an agroforestry-based subsistence farming system rarely occurs as a deliberate choice in the traditional farming systems in the semi-arid regions of Africa. However, in this particular environment in Sudan, in a landscape dominated by acacia trees, farmers do cultivate crops such as sorghum, millet or sesame under scattered trees, but not necessarily in a manner that truly integrates crops and trees in a pattern recognized as an agroforestry parkland system and practiced in the western Sudano-Sahelian region (cf. Bayala et al. 2014). Nevertheless, traditional systems that incorporate both trees and agricultural crops always have a potential to ensure a sustainable food security and improve livelihoods in rural communities across the African continent (Faye et al. 2010).

As is the case elsewhere with similar environmental and social settings, the success or failure of agricultural operations in the drylands of central Sudan depend much on the availability of seasonal labour with affordable cost for farmers and on the physical accessibility of the farms in question for seasonal labour (Pender and Gebremedhin 2008). To give a clear example, the vast majority of farmers in the semi-arid zone of Sudan (and, typically, in the El Dali area), frequently used migrant labour under terms of seasonality to execute such agricultural operations as crop harvesting. The obvious underlying and facilitating factor is that the seasonal labour could easily reach El Dali, unlike other areas with similar needs, because it is located relatively close to major towns. All roads that connect such important agricultural areas as those covered by the present study, El Dali and El Mazmum, with the main towns are in poor conditions. Especially during the rainy season when many of the agricultural activities take place, the roads are practically impassable.

Given the above, nonetheless, for many households, the scarcity of agricultural labour during the agricultural season is not always considered a major constraint because of a sufficient number of family members available to fulfil the needs in agricultural operations. This is the case since the affected households either may not have holdings large enough to require additional labour during the agricultural season, or, most likely, they have failed in obtaining a formal credit from concerned financial institutions such as the Agricultural Bank, to cover expenditures of farm activities including the cost of hiring seasonal labour (Ahmed et al. 2012).

Livestock management is a mainstay economic activity along with crop production for farmers in tropical as well as in temperate countries globally (FAO 2001). On the African continent, animal husbandry is considered being of paramount social importance and used to a lesser extent as an additional source of income to meet farmers' needs especially when crop yields fail.

Animals thus offer important means to bridge an income gap. However, in central Sudan there are often difficulties in finding sources for feeding the livestock, as no natural pastures may be available in the form of common land. Integrating animal husbandry with crop cultivation, for instance, in an agroforestry system, allows the livestock to forage on crop residues on each farmer's own farmland during the dry season; in addition, the animal manure thus available contributes as an organic fertilizer for crops. This type of mixed farming seems to be crucial for supporting the livelihoods of dryland farming communities (Delve et al. 2001, FAO 2001, Rufino et al. 2006).

5.2. The role of agroforestry in improving livelihoods (study I)

Today, food security is an extremely challenging problem and one of the priority development issues worldwide, as indicated by the UN Sustainable Development Goals that were adopted in 2015 (UN 2015). A growing world population increases the demand for food production very rapidly, even after the introduction of new agricultural technologies since the late 20th century. However, such technologies fail to improve land productivity especially in developing countries as long as many poor farmers are unable to reach them (Pimentel and Wightman 1998).

In recent times, research efforts in the agricultural field have been focusing on a diversity of means for ensuring food and nutrition security and poverty alleviation in general. Understanding of potential approaches requires knowledge of how factors on the farm and outside the farm contribute to food insecurity and consequently to the instability of livelihoods. Livelihood-related activities of rural people are divided into agricultural and non-agricultural and further into on-farm and off-farm activities (Barrett et al. 2001). The output in terms of cash generation among these different activities varies substantially. According to Buck et al. (1999), "*Agroforestry practice, the cultivation of trees or other woody plants with crops or pasture for multiple benefits, can contribute substantially to advancing a sustainable agriculture through its influence on ecological and social processes*". For the case of agroforestry parklands, for instance, there exists substantial and growing knowledge of the significance of scattered trees arising from natural regeneration among people who deliberately adopt such a system to improve their livelihoods (Bayala et al. 2014). In tropical drylands, while the water scarcity seriously impacts on livelihoods of up to millions of households, trees in agroforestry parkland systems play an important role in groundwater recharge and have a significant impact on the hydraulic properties of soil (Tobella et al. 2014).

A part of the present study attempts to explain and compare the impacts of different farming systems currently being practiced in the semi-arid areas of Sudan on people's livelihoods. It was found that the largest number of households, exceeding 78 percent of their total number, rely on multiple monoculture systems for securing their livelihoods. However, the remaining group, mainly consisting of leaseholders cultivating lands under fixed-term contracts with the government, depended on agroforestry parklands where their crops and/or animals were integrated with scattered natural trees such as *Acacia mellifera and A. senegal*, under a customary system of tree tenure.

In this study, perceived disparities in livelihoods between different types of households were further examined using analysis of crop yields and corresponding financial returns in different farming systems. This analysis, based on the 2001-2010 period, facilitated understanding of the differences between monoculture households and agroforestry-based households. In the latter system, the average yields of the three crops studied, sorghum, millet and sesame, were higher than those obtained from monoculture systems. This indicates that there is a substantial benefit obtained by households involved in cultivating agroforestry parkland systems, as compared to those who adopt a monoculture systems, an observation earlier presented by Fadl (2013). This result obviously offers guidance for finding an optimal farming system for the communities in question and for developing policies for its support. Perhaps most importantly, an improved system can rely on simply preserving the natural, scattered woody vegetation and using it as a component in a more or less permanent intercropping system (Boffa 1999, Bayala et al. 2014).

5.3. Determinants and limitations of agroforestry parklands (study II)

In semi-arid tropics, the most widespread agroforestry practices are silvo-pastoral or agro-silvo-pastoral systems that are based on integration of livestock with trees or crops, or both, on agrficultural lands. These may include many different practices such as homegardens, shifting cultivation, parklands, living fences or hedges that all used for specific local needs and purposes (Atangana et al. 2014). Parkland systems, in most cases, include agricultural practices that offer regular products such as food, fodder, fuelwood and utility or construction wood, in addition to improving the soil fertility and land productivity (Boffa 1999). This is attributed to the fact that the amount of nitrogen and phosphorus might be adequate under the canopy of such trees as *Faidherbia albida*, for which successful examples are found in Darfur in western Sudan as well as in the south-Sudanese zone of Burkina Faso (Miehe 1986, Gnankambary et al. 2008). On the other hand, unfavorable interactions between the components comprising the agroforestry system may also occur, for instance, as a result of competition for water (Gaafar et al. 2006).

There are several ecological, economic, cultural, or political constraints and other determinants that influence the adoption of agroforestry practices, i.e. the retention of agroforestry system components (trees, animals or crops) on the same piece of land. According to the present study, agro-climatic conditions, farm size, household family size, and incentives from agricultural associations are key drivers behind the occurrence of agroforestry on acacia parklands in the semi-arid zone of Sudan. In other areas it is also known that agro-ecological conditions influence the adoption of agroforestry systems (Nkamleu and Manyong 2005). A lack of incentives from the government prevented the farmers from properly adopting agroforestry practices. However, the farmers were very interested in receiving such incentives, for instance, in the form of secured land and tree tenure, improved access to extension services and planting materials, and re-arrangement of animal grazing on farmland (Russell and Franzel 2004, Glover and Elsiddig 2012).

In many studies, family size has also been found to be a decisive factor promoting tree planting, which commonly leads to adoption of an agroforestry system (cf. Irshad et al. 2011). However, in some cases, in addition to family or land holding size, the educational background of farmers and their environmental awareness or social interactions are factors that contribute to favouring agroforestry in a parkland systems (Muneer 2008). Overall, there appears to be a growing interest also in planting trees to form agroforestry systems for the benefit of future generations (cf. Sood and Mitchell 2009).

In the semiarid areas of Sudan there are parallel tendencies that uphold the adoption of agroforestry as well as a preference for monocropping systems, with an ultimate aim to improve the livelihoods in both cases. There is a general perception among both of these groups that agroforestry is constrained by such factors as land or tree tenure issues, limited farm size, the lack of planting materials and extension services, as well as animal movements on farmland. In addition, agroforestry practices are limited by complications associated with renting land for cropping. Intercropping with trees requires either a binding land lease contract or a secure land tenure for the farmer (Rao et al. 2016).

The likelihood of on-farm tree growing in a mixture with crops often increases when the farm size increases as well (Sood and Mitchell 2009). Similarly, the adoption of agroforestry systems frequently increases among farmers who keep contact with local extension agents. But more generally, in many regions worldwide, farm size is the most important factor that explains the variation in adoption of agroforestry (Muneer 2008, Dhakal et al. 2015).

5.4. Crop responses to climatic variability (study III)

A little more than half percent of the world's land surface is potentially suitable for rain-fed agriculture, while nearly 80% of agricultural production is obtained from rain-fed areas (Valipour 2013). Agricultural production under rainfall conditions is a risky choice due to the fact that most rain-fed areas are characterized by a high variability of rainfall caused by both intra-seasonal and inter-annual variations (Younis 1995). Farmers in rain-fed agricultural areas typically rely on their traditional knowledge for determining the proper time for sowing, due to lack of access to accurate weather information.

Increasingly, though, farmers are now more interested in obtaining precipitation forecasts, especially on the onset and end of the rainy season and on the potential instability of rainfall (Ingram et al. 2002). Such forecasts are of crucial importance for farmers who live in the African Sahel. Rain-fed agriculture remains the main provider of food to nearly 90% of the entire population in this region, whereas 89% of the cereals here come from rain-fed farming (Bationo and Buerkert 2001, Cooper 2004). It has been estimated that, in sub-Saharan Africa generally, rain-fed agriculture occupies more than 95% of all cultivated land (Laux et al. 2010). Crop yields respond to the variability of local weather conditions and to a predicted climate change, but, as also found in the present investigation, this response seems to be different from farm to farm even within a particular region.

The focus of the current study was on an analysis of annual yields of sorghum, millet and sesame crops produced in the low-rainfall semi-arid zone of Sudan, more precisely, at the El Dali and El Mazmum sites of Sinnar state. It was found that the variability of annual precipitation during the period 2001-2010 could quite well explain that variation in the yield of these crops in both situations, either within each site and between the two sites. Previous studies carried out in many regions in Africa have suggested that the yields of most food crops show significant declining trends, while an analysis of the annual precipitation even for a long period does not confirm any related trend.

In addition to the general decline of yields that does not seem to be caused by any long-term change in precipitation, the annual yield variations can be more attributed to inter-annual variability in rainfall (Moore et al. 2012, Traore et al. 2013, Goenster et al. 2015). A similar pattern of crop yield variability was found in the present study at the El Mazmum site for sorghum and millet which both showed gradually declining yields during the period 2001- 2010. In contrast, at the El Dali site, neither increasing nor decreasing trends were detected in crop yields between 2001 and 2010.

For the semi-arid zone of Sudan where the present study was carried out, it is reasonable to conclude that the inter-annual and intra-seasonal rainfall variability, together with the length of the rainy season, were the main factors influencing the variability of crop yields, with higher impact on sorghum and millet yields in at the El Mazmum site as compared to El Dali. These findings are in agreement with the observation that the drier the environment, the more crucial is the inter-annual and intra-seasonal rainfall variability for the success of farming in Africa, including Sudan (Omoyo et al. 2015).

5.5. Food security under land use change (study IV)

Global concern focuses currently on how to ensure food security for almost 10 billion people which is predicted to be the world population by 2050, while putting less pressure on land (Smith 2013). There is an urgent need to increase the food production, to up to about 70% above the current level (Verburg et al. 2013).

Agriculture provides the food security and livelihoods for the majority of, if not all, people living in the African semi-arid lands. Controversially, agriculture may also be considered as the main cause for deforestation and land degradation, as well as for reduced land fertility and productivity, all of which factors, in a vicious cycle, again seriously impact on the livelihoods of people living in those particular areas. In most instances, the conversion of forest lands to agricultural systems has, over a long time, led to the process of deforestation. In dryland Africa, the deforestation rate shows a linear positive correlation with agricultural expansion.

In fact, between 1990 and 2000, the practices of slash-and-burn farming contributed to about 83% of the deforestation occurring in Africa (Atangana et al. 2014). In the entire tropical zone approximately 55% of natural forests were converted to new farmland between 1980 and 2000; in addition, more than 27% of the new agricultural lands replaced disturbed forests during the same period (Gibbs et al. 2010).

The pattern of land use change driven by the expansion of agriculture looks fairly similar across the African continent. In East Africa, for instance, the disappearance of the woody vegetation cover is reported to negatively affect the soil chemical and physical properties, which in turn has serious consequences for food security at local, national and regional levels (Moore et al. 2012).

In Sudan agricultural expansion is also the main driver behind deforestation and forest degradation. In this country, about 17 million hectares of natural forests were replaced by mechanized and traditional rain-fed farming or irrigation schemes over a seven-decade period from 1940 to 2012, mainly due to an increased demand for food as a result of population growth (FCPF 2014). Thus, the expansion of rain-fed agriculture is explicitly viewed as the main cause for vegetation cover change across the semi-arid areas of Sudan from 1940 onwards (Sulieman 2010, Biro et al. 2013).

Many of the environmental, economic, social and political factors underlying the agricultural expansion and subsequent deforestation in these particular areas are common for all developing countries of the South. However, for Sudan generally, there are some specific drivers behind these processes which appear to be associated with factors that discourage farmers from managing agroforestry parkland systems. Specific for Sudan is the market situation for the most important non-wood forest product in the country, i.e. gum arabic; this commodity has suffered from very low producer prices, which contributes to neglect and even destruction of the gum-producing *Acacia senegal* trees. Additional factors undermining agroforestry practices include an unclear land tenure regime and a government policy that favours mechanised cultivation of agricultural crops, such as sorghum, for export.

In Sudan, agricultural lands have been stretched at an unprecedented rate on the expense of natural forests. Even more alarming is the fact that land productivity seems to have been decreasing to such an extent that there is a widening gap between the actual crop yields obtained and the potentially attainable ones; this has serious implications for food security (Ayoub 1999, Sulieman and Buchroithner 2009, Biro et al. 2013).

The present study confirms that, for dryland Africa in general and for Sudan in particular, agroforestry based on nitrogen-fixing leguminous trees offers the means for sustainable and even increasing agricultural production. The remaining challenge is to establish land use polices which allow farmers to maintain trees on their croplands and pastures – and to benefit economically from those trees – while also securing their land-use rights. The development of land ownership and land use rights in other contries of the Sudano-Sahelian zone offers a number of alternative models for agroforestry practices, many of which emphasize community action (for the cases of Burkina Faso and Niger, cf. Rij et al. 2009). In Sudan, earlier studies have demonstrated how different systems for community-based management of forests and trees have are already been tested in this country, but further policy development is also needed (Glover 2005). It has been suggested that stronger tree ownership may stop the conversion of natural forests to farmland (Verburg et al. 2013). As concluded by Moore et al. (2012), essential for any land policy reform is, however, to have a sufficient understanding of the processes of land use change and land cover change.

6. Conclusions and recommendations

The food security of people living in the semi-arid zone of Sudan is based on growing agricultural crops under rainfed conditions. Soil degradation is a common phenomenon and has led to a gradual continuous decrease in crop yields. This general decline was also observed in the present study area, the El Dali and El Mazmum locality in Sennar state for the period 2001-2010. No trend was found in the rainfall pattern, but there was large variation between years in annual precipitation, which seemed to be the main factor determining the crop yield. Agroforestry parklands produced the highest per-hectare yields of the three crops studied, sorghum, pearl milled and sesame, in comparison to monocropping.

Herbicide application for weed control was also studied, but it did not show any clear effects on crop yields, possibly due to low soil fertility and low general yield levels.

Even if integration of trees with crops showed positive effects on agricultural crop production, farmers were reluctant to adopt an agroforestry farming system because of several constraints, of which the insecurity of land use right was the most prominent. The effect of a number of socio-economic household characteristics on the willingness to practice agroforestry was analyzed, and it was found that farm size together with family size were positively correlated with the rate of adoption of agroforestry, while the lack of government incentives had a negative effect.

For the semi-arid regions of Sudan, efforts are needed for a land-use policy reform, especially for clarifying land and tree tenure issues and for minimising conflicts with livestock-herding migrant pastoralists. This would also restrain the ongoing process of conversion of forest land to farming.

The present study confirms the earlier results on the feasibility of agroforestry as a sustainable and productive dryland management model. In particular, it is recommended that the natural regeneration potential of dryland acacias is fully utilized, so as to create permanent agroforestry parklands which, apart from food, also would satisfy community needs for fuel, fodder, construction wood and non-wood forest products such as gum arabic.

Dryland farming is the backbone of livelihoods for the great majority of people in Sudan. For it to become more productive, attention must be paid to provision of extension services which incorporate both agricultural and forestry aspects of dryland management. Improved agricultural technologies, as well as banking services for financing the needed inputs, must also be provided.

Agricultural production based on rainfall in the semi-arid region of Sudan is threatened by climate variability, as indicated by the year-to-year differences in both precipitation and crop yields. Climate change scenarios commonly predict rising temperatures and decreasing precipitation. Agroforestry, as applied in the parkland system, has the advantage of providing a means for climate change adaptation by facilitating water and nutrient retention in the soil. Mineral fertilizers, when available, will also have a more pronounced positive effect on crop yields when the physical soil characteristics are improved by agroforestry management.

It can be concluded that global findings already show the potential of agroforestry systems in enhancing local climate change adaptation and in providing improved food security in rural areas. The present study reiterates that agroforestry systems based on the combination of agricultural crops and natural acacia trees need more attention in practical applications, as well as in research and development. In Sudan, the ultimate benefit is reduction of the vulnerability of the rural people in the semi-arid zone of the country.

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Annexes

Annex 1. Household questionnaire

A. General household data:

1. Household number:……. 2. Village name ………… 3. Date of interview ……………

4. Name of household head.……………………….. 5. Sex: M / F …………….

6. Martal status…………….6. Age…………years 7. Occupation…………………………

8. Educational level……………...9. Number of persons in household…………………..

B. Source of income

10. What is your source of income?
Farming (   ) Animal rearing (   ) Forest products (   ) Other, specify…………………….

11. If you have more than one source of income, define the primary and secondary sources?

Source of income	Primary	Secondary
Farm		
Animal production		
Forest products		
Other……………………		

12. What is your status of income security?
Highly unstable (   ) Seasonal fluctuation (   ) Stable (   ) Highly stable (   )

13. Do you have financial savings?
Yes (   )   No (   )

14. If yes, is it:
Low (   ) Moderate (   ) High (   )

C. Land use and the status of land and tree tenures

15. What is the type of your land tenure?
Leased holding (   ) Title holder (   ) Inherited land (   ) landless (   )

16. If you own land, what is the size of your land.............(ha)

17. If you are landless, what is the size of the land that you rent annually………(ha)

18. Do you have trees that form agroforestry intervention on your farmland?
Yes ( ) No ( )

19. If yes, estimate the number of trees/ha…………or ………./fa

20. What tree species are retained on your farmland?

…………………………………………………………………………………………………
....

21. Do you plant these trees or are they naturally regenerated?

Planted ( ) Naturally regenerated ( )

22. What is the status of trees on your farmland?
Secured ( ) Unsecured ( )

23. How are these trees arranged on your farmland?
Windbreak ( ) Strip ( ) Live fence ( ) Hedge rows ( ) Other, specify………………………………………………………………………………………

24. What constraints do you experience in practicing agroforestry intervention?
1………………………………………………………………………………………………
2………………………………………………………………………………………………
3………………………………………………………………………………………………
4………………………………………………………………………………………………
5………………………………………………………………………………………………

25. If you practice agroforestry, what model do you use?
Trees with crops ( ) Trees + crops + animals ( ) Trees with animals ( )

26. What are the main factors encouraging farmers to integrate trees with crops on their farmland?
1..
2..
3..
4..
5………………………………………………………………………………………………

27. If you practice an agropastoral system, what types of livestock do you have and how many of each?

Type of animal	Total number (head)
Cattle	
Sheep	
Goats	
Camels	
Other…………………	

28. What is your assessment of integrating animals with the farming system?

1. Improved land productivity ( )
2. Improved soil fertility vs. fallow period ( )
3. Improved livelihood e.g. additional source of income ( )
4. Other, specify…………………………………………………………

D. Crop production and field inputs

29. Which of the following tools do you use to prepare your land?
Machine ( ) Hand tools ( ) Animals ( ) Other, specify…………………

30. Which of these agricultural crops do you cultivate?
Sorghum ( ) Pearl millet ( ) Sesame ( ) Sun flower ( ) Groundnut ( ) Other, specify………………………………………………………………………………………

31. How do you finance your crop cultivation?
Self-finance ( ) Loan from Agricultural Bank ( ) Loan from other Banks ( ) Other, specify……………………………………………………………………………………...

32. What is your source of labour?
Family ( ) Recruit labour annually ( ) Both family and recruit labour ( ) Other, specify………………………………………………………………………………………

33. What reasons make you rely solely on your family as labour?
1……………………………………………………………………………………………
2……………………………………………………………………………………………
3……………………………………………………………………………………………
4……………………………………………………………………………………………

34. Do you follow rotation on your farmland?
Yes ( ) specify…………………….. No ( ) other methods………………………………

35. What crops do you use to secure your food and generate of income?

Crop	Food security	Generation of income	Both
Sorghum			
Millet			
Sesame			
Sun flower			
Groundnut			
………….			
………….			

36. From your viewpoint, which factors lead to increased or decreased land productivity?
1..
2..
3..
4..

37. Do you use herbicides for weed control?
Yes ( ) No ( )

38. If yes, which pesticides do you use?
………………………………………………...

39. Are these herbicides environmentally friendly?
Yes ( ) No ( ) I don't know ( )

40. If no to question 37, specify the constraints to herbicide application
1……………………………………………………………………………………………..
2……………………………………………………………………………………………..
3……………………………………………………………………………………………..
4………………………………………………………………………………….............

41. Do you use fertilizers to increase crop production?
Yes ( ) No ( )

42. If yes, which fertilizers do you use?
………………………………………………………………………………………………

43. Are these fertilizers environmentally friendly?
Yes ( ) No ( ) I don't know ( )

44. If no to question 40, specify constraints to fertilizer application
1…………………………………………………………………………………………….
2……………………………………………………………………………………………
3……………………………………………………………………………………………
4……………………………………………………………………………………………

45. From your estimated records, what is the total production gained from your farmland (sack/ha) during the past decade.

Crops	2010	2009	2008	2007	2006	2005	2004	2003	2002	2001
Sorghum										
Sesame										
Millet										
Sunflower										
………..										
……….										

46. What tools have you used to harvest the crops?
Rudimentary hand tools *manual* ( ) modern tools *machinery* ( )

E. Household expenses (SDG/ha) for crop cultivation

47. How much do you estimate to have spent on the following operations during the last decade?

Operation	Total cost (SDG/ha)									
	2010	2009	2008	2007	2006	2005	2004	2003	2002	2001
Land preparation										
Seeds										
Weeding										
Rent ha to government										
Rent ha to land owner										
Herbicides										
Empty sacks										
Sorghum harvesting										
Millet harvesting										
Sesame harvesting										
………harvesting										
Other costs……….										

F. Household income

48. What is your estimated income for the following crops during the last decade?

Crops	Price (SDG/sack/crop)									
	2010	2009	2008	2007	2006	2005	2004	2003	2002	2001
Sorghum										
Millet										
Sesame										
Sun flower										
…………..										
…………..										

G. Energy and housing construction of household

49. What is your source for energy and housing construction?

Source	For energy	For housing construction
Reserved forests		
Natural woodland forests		
Private forests		
Community forests		
Trees grow on own farmland		
From market		
Other……………………..		

50. If you collect you wood from forests, how is it possible?
1. FNC allows collection of dead branches and trees ( )
2. Through wood for work ( )
3. Under certain condition (fire accidents) ( )
4. Other, please specify…………………………………….. …..........

51. Is it possible to be involved in the participatory management of the forests?
Yes ( ) No ( ) I don't think so ( )

52. If yes, which jobs can you participate in?
1. Seedlings production at nursery ( )
2. Protection of new regenerations from livestock ( )
3. Weeding, thinning, harvest, other ( )
4. Other, specify……………………………………………. ………..

53. Through participating in forest activities do you feel that?
1. Your awareness has increased towards the trees ( )
2. Trees are important for multipurpose uses ( )
3. Trees provide a source of income during the off-season ( )
4. Trees are the main source for feeding animals during the dry season ( )
5. Other, specify…………………………………………………………

H. Land-use policy reform and tree tenure

54. Do incentives and subsidies encourage the adoption of trees?
Yes ( ) No ( )

55. For any answers please mention the reasons:
....
....
....
....

56. Do current land-use policies and legislations pose constraints to securing your livelihood?
Yes ( ) No ( )

57. Do you expect that the government and/or policymakers will reform the land-use policy and land rights towards securing livelihoods and encourage individual land rights?
I believe so ( ) I don’t believe so ( ) No change will be made in the future ( )

Annex 2. Rainfall data during the period 2000–2010 for the El Dali and El Mazmum localities

بسم الله الرحمن الرحيم

ولاية سنار

وزارة الزراعة والثروة الحيوانية والري

إدارة القطاع المطري

جملة الأمطار بالملميتر من موسم 2000 -2011 م لمحلية الدالي والمزموم

المزموم	الدالي	العام
كمية الأمطار/ملم	كمية الأمطار/ملم	
582,2	623,4	2000م
586	668	2001 م
389	465,9	2002 م
662,2	601,5	2003 م
465,9	316,4	2004 م
404,9	658,6	2005 م
334,5	436	2006 م
612,2	565	2007م
468,7	602	2008 م
520,1	464	2009 م
650	337	2010 م
695,5	439,7	حتى2011/9/29 م

وجزاكم الله خيرا

ولاية سنار

التاريخ 29-9-2011

29/9 2011

حسين آدم عبدالله ابراهيم

مدير إدارة القطاع المطري والمشاريع الرائدة

Annex 3. Demarcated and undemarcated agricultural schemes (fa)* of the El Dali and El Mazmum localities

بسم الله الرحمن الرحيم

ولاية سنار

وزارة الزراعة والثروة الحيوانية والري

إدارة القطاع المطري

تفـــاصيل مساحــــات الزراعة بالقطاع المطري (مخطط ،جمعيات ،خارج تخطيط ،تقليدي وتقنين) لمحلية الدالي والمزموم

الوحدة الإدارية	المساحة الكلية/فدان	تفاصيل المساحة المخططة/ فدان			تفاصيل المساحة غير المخططة /فدان		
		المخطط أفراد	شركات	جمعيات	خارج التخطيط	تقليدي	تقنين
المزموم	897482	488529	55000	19000	275977	45260	13716
الدالي	545123	299421	-	13000	169148	27740	35,814

وجزاكم الله خيراً

29/9/2017

حسين آدم عبدالله ابراهيم

مدير إدارة القطاع المطري والمشاريع الرائدة

*1 feddan (fa) = 0.38 ha

No. 15 Mustafa, A. F. 1997. Regeneration of *Acacia seyal* forests on the dryland of the Sudan clay plain. Doctoral thesis.

No. 16 El Fadl, M. A. 1997. Management of *Prosopis juliflora* for use in agroforestry systems in the Sudan. Doctoral thesis.

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