Bal Ram Singh · Andy Safalaoh
Nyambilila A. Amuri · Lars Olav Eik
Bishal K. Sitaula · Rattan Lal *Editors*

Climate Impacts on Agricultural and Natural Resource Sustainability in Africa

Springer

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Foreword

Climate change and sustainable management of natural resources remain the major issues for all interventions to improve agricultural production, food access, and agriculture-based livelihoods in sub-Saharan Africa (SSA). Agriculture in SSA is predominated by small farms and subsistence farming by hand tools and limited use of other inputs including fertilizers, pesticides, and irrigation. There is also an increasing concern on declining land resources due to rapid soil degradation, harsh and uncertain climate, and the rapidly increasing population. Population of 800 million in 2010 is projected to increase to 1.1 billion in 2020 and to 1.8 billion in 2050 in Africa.

Despite these limitations, signs of agronomic yield increases and noticeable promise with impressive annual growth rates have been observed. However, sustaining the growth rate will become harder in the future due to increasing population, warmer climate, limited water resources, soil erosion and contamination, and more pervasive pests and pathogens. Furthermore, the IPCC Special Report on Global Warming indicates an increase of 1.5 °C change in temperature in SSA, creating a threat to ecosystems, biodiversity, and human health. These threats are more challenging and apparent in SSA than elsewhere. These challenges create a need of generating new knowledge on natural resource management and climate change to provide an enabling environment for smallholder farmers for engaging in sustainable agricultural practices.

Recognizing the value of agricultural production, the problems of natural resource degradation, and the challenge of climate change in SSA, a project entitled "Capacity Building for Managing Climate Change in Malawi" (CABMACC) was supported by the Royal Kingdom of Norway and implemented during the period 2013–2018. The Lilongwe University of Agriculture and Natural Resources (LUANAR) and the Norwegian University of Life Sciences (NMBU) jointly implemented the program. CABMACC was aimed to strengthen the teaching, training, research, technology development, and outreach for climate change adaptation and mitigation planning. A long-term and outstanding collaboration of LUANAR, NMBU, and Sokoine University of Agriculture (SUA) is further extended in this knowledge and experience-sharing platform to enhance dissemination of research findings from CABMACC project and beyond. The research under the abovementioned project focused primarily in Malawi, and therefore, contributors beyond the project were invited to cover wider geographical regions and their physical and social heterogeneities.

This book, *Climate Impacts on Agricultural and Natural Resource Sustainability in Africa*, deals with both the natural science and social science aspects, under dwindling natural resources, changing climate, and increasing climate uncertainties in SSA.

We convey our thanks to the successful authors, editors, and reviewers of the chapters in this book. We believe that the knowledge presented here is a crucial piece in the ingredients required for sustainable resource management under changing and uncertain climate in SSA.

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Preface

Most countries in sub-Saharan Africa (SSA) are dependent primarily on agriculture for economic growth and livelihoods. Majority of the households, especially rural smallholder farmers, are perpetually food insecure due to unsustainable practices in agriculture, degrading agroecology, poor natural resource management, and political and institutional challenges. Agriculture in SSA countries is dominated by small farms, often less than 2 ha, and is primarily based on hand tools and manual operations with limited use of farm machinery and soil amendments, insufficient supplemental irrigation, and inadequate measures for soil and water conservation.

The harsh and changing climate has further aggravated the situation, adversely affected the natural resources, jeopardized agricultural production, and marginalized the livelihood opportunities. Adverse effects of climate change on agricultural production and the environment have made the SSA region as one of the hot spots leading to severe degradation of soil, drastic depletion of nutrients and soil organic matter stocks, water scarcity and contamination, and reduction of the above- and below-ground biodiversity.

The overall goal of the project "Capacity Building for Managing Climate Change in Malawi" (CABMACC) was to improve livelihoods and food security through innovative responses and enhance the capacity of adaptation to climate change. It was conducted at the Lilongwe University of Agriculture and Natural Resources (LUANAR) in Malawi in cooperation with the Norwegian University of Life Sciences (NMBU). The project was implemented in several districts of Malawi, which are considered the hot spots for climate change-related vulnerability.

To deliberate some of the challenging issues stated above, an international conference on Sustainable Agriculture and Natural Resource Management under Changing Climate in sub-Saharan Africa was organized at LUANAR, Lilongwe, Malawi, from 16 to 18 October 2018. The conference was an avenue to bring in researchers who conducted research in SSA and share findings that can be documented to provide scientific evidences to form policies to attain sustainable agriculture and natural resource management under changing climate. The major objectives of the conference were to bring new knowledge on sustainable use of natural resources to enhance agricultural productivity under changing climate and explore new avenues of policies, value added chain, and adoption of innovative technologies on smallholder's farms.

The 34-chapter book represents the oral presentations made during the conference. The book includes, in addition to introductory and concluding chapters, five thematic parts, namely, (i) Conservation Agriculture, Carbon Sequestration, and Soil and Water Management, (ii) Sustainable Crop/Livestock/Aquaculture/Fish Production, (iii) Policy and Institutions for Sustainable Agriculture and Natural Resource Management, (iv) Value Added Options for Smallholder Market Access and Integration, and (v) Upscaling Innovative Technologies on Smallholder Farms.

Nearly 150 participants attended the conference from Malawi, Rwanda, Ethiopia, Tanzania, Kenya, Norway, and the USA. The steering committee involved in the organization of the conference included representatives from LUANAR, Malawi; NMBU, Norway; Ohio State University (OSU), USA; and Sokoine University of Agriculture (SUA), Tanzania. The conference was a concluding activity of the project "CABMACC" in Malawi funded by the Royal Kingdom of Norway.

We, the editors, wish to thank all the authors for their outstanding contributions for the book. We also thank the staff at Springer for following the proposed publication schedule and bringing out the publication on time. Our special thanks are due to PCO staff at LUANAR for their help in the organization of the conference and managing the flow of manuscripts between the authors and the editors.

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Part III Sustainable Crop/Livestock/Aquaculture/Fish Production

Editors Biographies

Bal Ram Singh, PhD is a professor emeritus at the Norwegian University of Life Sciences. He earned his PhD degree from G.B. Pant University of Agriculture and Technology, India. His program focuses on bioavailability and mobility of heavy metals in the soil and plant system, fertility management and agricultural sustainability in soils of the tropics, and carbon sequestration in soils. He has served as chairman of the program board "Soils and Plants" of the Research Council of Norway and as deputy head of the Department, in addition to many national and international committees. He chaired the Cost Action FA0905 (EU) "Mineral Improved Crop Production for Healthy Food and Feed," in which more than 200 scientists from 31 countries participated. He has supervised 76 graduate students and 16 visiting fellows/scientists from 20 countries and published 456 articles, of which 260 are in peer-reviewed journals and books. He is a fellow of ASA (2004) and SSSA (2005) and recipient of the International Soil Science Award (SSSA) in 2011. He is currently chair of Division 3 of the International Union of Soil Science, president of the Norwegian Society of Soil Science, and member of the Geomedicine Committee – Food, Environment, and Health of the Norwegian Academy of Science and Letters.

Andy Safalaoh, PhD is an associate professor of Animal Nutrition at the Lilongwe University of Agriculture and Natural Resources (LUANAR), Lilongwe, Malawi. He earned his PhD degree in Science and Technology Studies from the University of Nottingham, UK, and his Master of Science in Animal Science from Oklahoma State University, USA. His research interests focus on nutrient evaluation of unconventional feedstuffs such as sorghum and millet and recently on the use of insects as feeds. In addition, he has developed interest in the development and exploration of climate-resilient agricultural technologies and innovations as instruments for climate change adaptation and mitigation with a focus on the food-feed nexus. He has previously served as deputy head, Animal Science Department, and postgraduate and seminar coordinator and chairperson, Research and Publications Committee, LUANAR. He is currently the university program coordinator at LUANAR and has been leading the implementation of the 5-year (2013–2018) Norwegian Government-funded Capacity Building for Managing Climate Change in Malawi (CABMACC) Program and other projects. He is also a Leadership in Environment and Development (LEAD) Cohort 12 fellow (2004), Imperial College London. At regional level, he has facilitated several training sessions on agriculture, science, technology, and innovation (ASTI) in collaboration with Technical Centre for Agricultural and Rural Cooperation (CTA), Wageningen, Netherlands, and under the RAEIN-Africa Innovation Systems Approach Competency Building Training Program in eight countries. Before joining the university, he worked with Save the Children USA-Malawi Country Office in various portfolios as training and development coordinator, food production coordinator, and program manager.

Nyambilila A. Amuri, PhD is a senior lecturer at Sokoine University of Agriculture (SUA), Morogoro, Tanzania. Currently, she serves as a coordinator for research and publication and head of Department of Soil and Geological Sciences at SUA. She earned her PhD in Soil Science from the University of Arkansas, Fayetteville, USA, and her Bachelor of Science in Horticulture and MSc in Soil Science and Land Management from SUA, Morogoro, Tanzania. Her research, university teaching, and outreach experience and interest are on C and N dynamics and residue management in agricultural soils, integrated soil fertility and agroecological management, appropriate fertilizer uses in agriculture, agronomic micronutrient fortification and mineral nutritive quality of food crops, site-specific fertilizer recommendations and innovative and cost-effective soil testing methods, and soil chemistry. Currently, she serves as a secretary general for the Soil Science Society of East Africa (SSSEA) and also chaired East Africa Fertilizers and Soil Conditioners of the Agriculture and Agrochemicals Technical Committee. She has supervised 17 graduate students and published 50 papers in peer-reviewed journals, conference proceedings, chapters in books, and extension manuals. She is a recipient of the Fulbright Scholar Award, Margaret MacNamara Memorial Fund Award, and NORAD Sponsorship Award.

Lars Olav Eik is a professor at the Norwegian University of Life Sciences (NMBU) specialized in animal nutrition and small ruminant production systems. After graduating from NMBU, he joined Sokoine University of Agriculture (SUA), Tanzania, working on dry season feeding of ruminants and introduction of dairy goat keeping in Tanzania. After this assignment, he returned to NMBU and completed his PhD based on work with dairy goats in Norway.

Since 2005, he has coordinated three major research programs in collaboration with SUA. He has also participated in research projects in Ethiopia, Malawi, and South Africa. Often working together with farmers and private sector, his main interest is developing multifunctional production systems and value chains for small ruminants, both in tropical and temperate regions. He has supervised a number of PhD students, particularly from East Africa. His teaching covers small ruminant nutrition and production systems and tropical animal husbandry and aquaculture.

Bishal K. Sitaula, PhD is a professor at the Norwegian University of Life Sciences, where he earned his PhD degree. His program focuses on various institutional collaboration programs in higher education and research in South Asia, Africa, and Western Balkan. His international collaboration experiences in diverse environmental and development issues, in inter- and multidisciplinary framework, mainly focus on ecological and socioeconomic issues influencing the environment and global changes. The specific topics covered are anthropogenic influences in soil water and air, land use and changes, agricultural intensification, GHG fluxes from land uses, carbon dynamics, land degradation, system analyses, environmental education, conflict, peace and development studies including wisdom and personal transformation relevant for ecosystem management, and global change and development. He has field research experiences from Europe, Asia, Africa, and North America through institutional collaboration, educational program, and networking projects with national and international organization. He has various program leadership experiences. He has contributed in developing various educational program and course curricula and created several educational documentary films. Despite more than 190 scientific publications, he has wider public engagements/social work with extensive delivery of public talks with media coverage.

Rattan Lal, PhD is a distinguished university professor of Soil Science and director of the Carbon Management and Sequestration Center, Ohio State University, and an adjunct professor of the University of Iceland. He was president of the World Association of Soil and Water Conservation (1987–1990), International Soil and Tillage Research Organization (1988–1991), Soil Science Society of America (2006–2008), and International Union of Soil Sciences (2017–2018). His professional research interests include soil carbon sequestration for food and climate security, conservation agriculture, principles and practices of soil erosion control, eco-intensification of agroecosystems, soil restoration, and sustainable management of soils. He authored 950 journal articles, authored/edited 100 books, mentored 350 researchers, has 144 h index and total citations of 95,000, and is editor of the *Advances in Soil Science* and *Encyclopedia of Soil Science*. He is laureate of the GCHERA World Agriculture Prize 2018, Glinka World Soil Prize 2018, and Japan Prize 2019.

Yield and Profitability of Cotton Grown Under Smallholder Organic and Conventional Cotton Farming Systems in Meatu District, Tanzania

T. N. Bwana, Nyambilila A. Amuri, E. Semu, J. E. Olesen, A. Henningsen, M. R. Baha, and J. Hella

Abstract Agronomic practices have a large effect on the yield and profitability of low-input smallholder cotton farming in Africa. A two-season field experiment was conducted in a semi-arid cotton growing area in Meatu District, Tanzania, to compare the yield and profitability of various conventional and organic cotton production practices. Besides the currently applied low-input conventional and organic cotton production practices, higher-input and innovative farming practices as well as control treatments (without fertiliser or pesticides) were tested. While season 1 had weather conditions that were very suitable for cotton production, much less

AH, NAA and JEO formulated the general research question and initiated the research project; TNB, NAA, ES and JEO formulated the specific research questions and designed the field experiment; TNB, supervised by NAA, ES, and JEO, conducted the field experiment and collected the data; TNB and AH conducted the economic analysis; AH conducted the statistical analysis; JH and MRB provided information about economics and politics of cotton production in Tanzania; TNB drafted the chapter and AH added and rewrote some paragraphs. All authors contributed to the revision of the chapter.

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rainfall in season 2 severely reduced the yield and land rent in both conventional and organic cotton production. In general, conventional and organic practices have similar cotton yields, but organic practices often generate higher land rents than conventional practices due to a higher price for organic cotton and lower production costs. In both seasons, the innovative organic practice generated the highest land rent of all conventional and organic practices, and it is statistically significantly higher than the land rents of all conventional farming practices.

1 Introduction

Cotton *(Gossypium hirsutum* L.) is the second largest export crop in Tanzania (after coffee) and largely contributes to national export earnings. Furthermore, it provides employment and income for over 500,000 households in rural Tanzania (TCB 2010). Cotton growing in Tanzania is dominated by smallholder farmers with farm sizes ranging from 0.5 to 10 hectares, with an average of 1.5 hectares. The production is characterised by manual operation under rain-fed conditions with minimal use of inputs such as fertilisers and pesticides. Two cotton production systems, conventional and organic, are practised in Tanzania, with the majority of cotton farmers practicing the conventional system (TCB 2010). Conventional cotton farming is based on the use of inorganic fertilisers and synthetic pesticides (Pimentel et al. 2005). However, most conventional smallholder farmers use little or no fertiliser, but they appreciably use pesticides for controlling the common cotton pests like aphids [*Aphis gossypii* (Glover)], American bollworm [*Heliothis armigera* (Hubner)] and cotton stainer [*Dysdercus* spp.].

The recommended application rates for fertiliser in cotton production vary depending on the soil type. For the Western cotton growing area (WCGA) of Tanzania, the revised fertiliser recommendations show application rates of 20–30 kg N ha^{-1}, 10–15 kg P ha^{-1} and 5 Mg ha^{-1} farm yard manure (FYM) (Mowo et al. 1993). However, a general national recommended rate of 40 kg N ha^{-1} and 18 kg P ha^{-1} is also reported by IFDC (2014). No specific national recommendations for pesticide use in cotton are available, and the application rates are based on guidelines from the pesticide manufacturers, which suggest four to six sprays per growing season.

Organic agriculture is a farming system that does not use genetically modified organisms (GMO), inorganic fertilisers, synthetic pesticides or any other agrochemicals (FAO 1998; Gold 2007; IFOAM 2014) but largely relies on soil fertility management for nutrient supply and natural pesticides for pest control. In recent years, organic cotton production in Tanzania has increased. In the season 2017/18, for example, Tanzania produced 3525 Mg of organic cotton, which placed the country in the seventh position of the world's leading organic cotton producers and in the second position in the world regarding the land area that is under conversion to organic cotton production (Textile Exchange 2018). Organic cotton production is practised in some areas in the Western cotton growing area, like Meatu and Maswa districts in Simiyu Region and in Singida Region. The production is contract based, where farmers enter production contracts with private companies. The contracting company provides organic seeds and biopesticides and offers training and extension services. In turn, the company is entitled to purchase the entire crop. The organic cotton production practices for nutrient management include the use of FYM, crop rotation and intercropping with legumes. For pest management, the practices also include trap crops (e.g. intercropping with sunflower) and the use of organic pesticides (neem-leaf extract or pyrethrum). However, there is no local documented information on agronomic, economic and environmental performance of these practices.

The average seed cotton yields in Tanzania fluctuated between 427 and 766 kg ha^{-1} 5–10 years ago but have decreased to 199–367 kg ha^{-1} in 2015/16 to 2018/19 (see Table 1; TCB 2019). This low yield is associated with major yield-limiting factors such as rain-fed growing conditions with infrequent rainfall, use of low yielding varieties and insufficient use of fertiliser and pesticides (TCB 2010). The Tanzanian government aims at increasing cotton production by 30% every year, initially aiming at increasing cotton yield from 750 kg ha^{-1} seed cotton (260 kg ha^{-1} of lint) in 2016/17 to 1500 kg ha^{-1} (520 kg ha^{-1} of lint) by 2020/21 (TCB 2016). The strategy for achieving this target includes several initiatives, e.g. building research capacity in various aspects of cotton farming, especially the breeding of new varieties and control of diseases and pests; establishing a participatory planning process for all stakeholders in the cotton sector; ensuring that all cotton production in the WCGA is done as contract farming; and establishing links among all relevant actors within the cotton value chain (e.g. extension service, input suppliers, farmers, cotton traders, ginneries) (TCB 2016). However, extensive use of inputs (fertilisers and pesticides) in these strategies is also associated with negative environmental impacts, such as nutrient losses causing eutrophication in water bodies, biodiversity loss, greenhouse gas (GHG) emissions, soil acidification and land degradation (Gomiero et al. 2011).

Table 1 Cotton production in Tanzania: area, production and yield

Season	Area (ha)	Production (Mg)	Yield (Mg ha^{-1})
2009/10	411,065	267,004	0.650
2010/11	382,934	163,518	0.427
2011/12	481,719	225,938	0.469
2012/13	465,996	357,133	0.766
2013/14	389,733	242,138	0.621
2014/15	455,272	202,312	0.444
2015/16	447,328	149,913	0.335
2016/17	423,341	122,362	0.289
2017/18	668,685	132,961	0.199
2018/19	607,029	222,725	0.367

Source: TCB (2019) and own calculations based on TCB (2019)

Among agricultural practices, organic farming practices are perceived to be more environmentally benign than conventional farming because of the avoidance of inorganic fertilisers and synthetic pesticides and the reliance on organic nutrient cycles (Tuomisto et al. 2012; Lorenz and Lal 2016). However, it remains unclear how the crop yields and economic performance compare between organic and conventional systems for crops grown under smallholder production systems in sub-Saharan Africa (SSA). Some authors argue that organic farming systems have lower yields than conventional farming and hence would not be able to meet the world's growing food demand (de Ponti et al. 2012). They also argue that organic farming is associated with low labour productivity, high production risks and high costs due to additional costs of certification (Borlaug 2000; Trewavas 2001; Nelson et al. 2004; Makita 2012). Others argue that under good management, yields from organic farming can be similar to or greater than those of conventional farming (Cavigelli et al. 2009; Seufert et al. 2012).

Most studies comparing yields of organic and conventional farming practices have been done in temperate climates (Rosenstock et al. 2013), leaving a wide data gap for tropical and subtropical conditions. This advocates for comparisons of the two farming systems in SSA in order to be able to give recommendations for sustainable cotton production in the region (Richards et al. 2016). As farmers often choose the production method according to their profitability, it is important that these comparisons extend beyond agronomic performance such as yield and also include profitability indicators such as the land rent. This study assesses the yields and land rents of cotton grown under low-input smallholder conventional and organic production systems.

2 Materials and Methods

2.1 Study Site Description

The field experiment was conducted in the Meatu District, Simiyu Region in Tanzania. The area is between latitudes 3°–4° S and longitudes 34°8′–34°49′ E at an altitude of 1000–1500 m.a.s.l. The area is within the semi-arid zone; rainfall ranges from 900 mm per year in the north to 400 mm in the south. The soil type at the experimental site was described to family level by Bwana (2019) as almost flat, moderately deep, clayey, moderately to strongly alkaline isohyperthermic, Pachic Calciustolls as per the USDA Soil Taxonomy (Soil Survey Staff 2014) and as Sodic Pellic Vertisols (Hypereutric, Mazic, Mesotrophic) according to the World Reference Base for Soil Resources (WRB) (IUSS Working Group WRB 2015). Crop and livestock farming are the major economic activities (URT 2017). Cotton is the main cash crop in the area where both conventional and organic cotton production is practised. Green gram (*Vigna radiata* (L.) R. Wilczek) is widely grown in the area and used in cotton-legume rotations and to some extent for intercropping with cotton. The study was done at BioRe Tanzania Ltd.'s demonstration farm, Mwamishali

Village, located at 3°31′11″ S and 34°14′05″ E, for two consecutive cotton growing seasons, season 1 (2015/16) and season 2 (2016/17).

2.2 Experimental Plot Initial Soil Properties

A composite soil sample was collected prior to our experiment at a depth of 0–20 cm, air-dried and sieved through a 2-mm sieve and analysed to determine initial soil properties. The composite sample was used to determine soil texture by the hydrometer method (Day 1965), and textural classes were determined using the USDA textural triangle (Soil survey staff 2014). The soil pH and electrical conductivity were determined by the potentiometric method (Okalebo et al. 2002*).* Organic carbon was determined by the Walkley and Black wet oxidation method (Nelson and Sommers 1982), total nitrogen by the Kjeldahl wet digestion-distillation method, extractable P by the Bray-1 method (Olsen and Sommers 1982), cation exchange capacity for basic cations (Ca, Mg, K and Na) by the NH_4OAc saturation method (Thomas 1982) and micronutrients (Cu, Fe, Zn, Mn) by the diethylenetriaminepentaacetic acid (DTPA) method (Motsara and Roy 2008). Undisturbed soil samples were also collected by using a core ring at the depth of 0–20 cm to determine soil bulk density and porosity by the core method (Blake and Hartge 1986).

In summary, initial soil properties of the experimental field consisted of a sandy clay texture (38% clay) and a soil pH of 9.0 and 7.2 in H_2O and $CaCl_2$, respectively; organic carbon was 1.03%; total nitrogen was 0.14%; extractable phosphorus was 16.0 mg kg^{-1}; and exchangeable bases in cmolc kg^{-1} were 17.87, 3.47, 1.54 and 0.11 for Ca^{2+}, Mg^{2+}, K^+ and Na^+, respectively. Micronutrient concentrations were 1.44, 1.11, 0.40 and 9.12 mg kg^{-1} for Cu, Fe, Zn and Mn, respectively. The bulk density was 1.36 g cm^{-3} and the soil is rated marginally suitable for cotton production due to low soil fertility (Bwana 2019). The manure used had an organic carbon content of 8%, total nitrogen of 1.03%, extractable phosphorus of 103 mg kg^{-1} and a C/N ratio of 7.8.

2.3 Weather Data

Weather data were recorded hourly using an automatic weather station (AWS) installed at the experimental site at the beginning of the experiment. The AWS collected data on precipitation, measured with an ECRN-100 high-resolution rain gauge (Decagon Devices Inc.). Air temperature and humidity were measured by a VP-4 sensor (Decagon Devices Inc.), solar radiation was measured by a PAR sensor, and soil temperature and moisture were measured by a 5TM sensor (Decagon Devices Inc.) at 20-cm depth. Hourly averages were logged in an Em50 data logger (Decagon Devices Inc.). The soil water-filled pore space (WFPS) was calculated from the measured volumetric soil moisture (VWC) using the relation WFPS (%) = 100 ∗ VWC ∗

$(1–BD * PD^{-1})^{-1}$, where BD = bulk density and PD = particle density, where the particle density (PD) was assumed to be 2.65 g cm^{-3} (Brady and Weil 2014).

2.4 Field Experimental Design and Treatments

A field experiment was conducted over two consecutive growing seasons, 2015/16 and 2016/17. The agronomic and economic performance of cotton was tested under a range of fertilisation and pest control strategies for both conventional and organic farming. As described in Tables 2 and 3, the current low-input conventional and organic cotton farming practices were tested against higher application rates and innovative practices, as well as against control treatments without fertilisers or pesticides. For conventional fertilisation management practices, two application rates of nitrogen (N) from the inorganic fertilisers diammonium phosphate (DAP) and urea and an innovative practice of combining inorganic fertilisers and organic manure were tested. For organic farming, the fertility management practices include two different levels of organic manure and an innovative practice of intercropping cotton and green gram.

Table 2 Soil fertility management treatments

Management	Treatments	Description	
		At planting	Later in the season
Conventional	*CF-0* – No fertilisers	No fertilisation	No fertilisation
	CF-30 – Currently practised fertilisation: 30 kg N ha^{-1}	75 kg ha^{-1} DAP (13.5 kg N ha^{-1}, 15 kg P ha^{-1})	At squire formation, top-dress with 35.9 kg ha^{-1} urea (16.5 kg N ha^{-1})
	CF-60 – Higher fertilisation rate: 60 kg N ha^{-1}	100 kg ha^{-1} DAP (18 kg N ha^{-1} + 20 kg P ha^{-1})	At squire formation, top-dress with 91.4 kg ha^{-1} urea (42 kg N ha^{-1})
	CF-30 + M – Innovative fertilisation: 3 Mg ha^{-1} FYM + 30 kg N ha^{-1}	3 Mg ha^{-1} FYM	At squire formation, top-dress with 65.2 kg ha^{-1} urea (30 kg N ha^{-1})
Organic	*OF-0* – No fertilisers	No fertilisation	No fertilisation
	OF-3 – Currently practised fertilisation: 3 Mg ha^{-1} FYM	3 Mg ha^{-1} FYM	No fertilisation
	OF-5 – Higher fertilisation rate: 5 Mg ha^{-1} FYM	5 Mg ha^{-1} FYM	No fertilisation
	OF-3 + L – Innovative fertilisation: 3 Mg ha^{-1} FYM + intercropping with green gram	3 Mg ha^{-1} FYM	At 2–4 weeks after planting cotton, plant green gram (*Vigna radiata*) between cotton rows

Table 3 Pesticide treatments

Management	Treatments	Description
Conventional	*CP-0* – No pesticides	No pesticide application
	CP-3 – Currently practised pesticide application: 3 sprays with synthetic pesticide	Each application: 371 ml ha^{-1} Ninja (50 g l^{-1} lambda-cyhalothrin) (in total: 1.112 l ha^{-1} Ninja)
	CP-6 – Higher pesticide application rate: 6 sprays with synthetic pesticide	Each application: 371 ml ha^{-1} Ninja (50 g l^{-1} lambda-cyhalothrin) (in total: 2.224 l ha^{-1} Ninja)
	CP-3-N + CU – Innovative pesticide application: 3 sprays with neem-leaf extract + cow urine	Each application: 24.8 kg ha^{-1} fresh neem leaves +3.5 l ha^{-1} sunflower oil +5.0 l ha^{-1} cow urine (in total: 74.3 kg ha^{-1} fresh neem leaves +10.4 l ha^{-1} sunflower oil +14.9 l ha^{-1} cow urine)
Organic	*OP-0* – no pesticides	No pesticide application
	OP-P – currently practised biopesticide application: Pyrethrum according to scouting	Scouting determines number and date(s) of sprays (season 2015/16: 1 application; season 2016/17: 1 application). Each application: 272 ml ha^{-1} natural Pyrethrin extract
	OP-N – innovative biopesticide application: Neem-leaf extract according to scouting	Scouting determines number and date(s) of sprays (season 2015/16: 1 application; season 2016/17: 1 application). Each application: 24.8 kg ha^{-1} fresh neem leaves +3.5 l ha^{-1} sunflower oil
	OP-N + CU – innovative biopesticide application: Neem-leaf extract + cow urine according to scouting	Scouting determines number and date(s) of sprays (season 2015/16: 1 application; season 2016/17: 1 application). Each application: 24.5 kg ha^{-1} fresh neem leaves +3.5 l ha^{-1} sunflower oil +5.0 l ha^{-1} cow urine

For conventional farming, the tested pest management practices included the currently practised three sprays with a synthetic pesticide (Ninja, 50 g l^{-1} lambda-cyhalothrin), a higher application rate of six sprays with the same synthetic pesticide and an innovative practice with three sprays with neem-leaf extract and cow urine. For organic farming, the pest management practices included the currently practised application of natural pyrethrum extract, application of neem-leaf extract and application of a mixture of neem-leaf extract and cow urine. The neem-leaf extract was prepared by soaking pounded fresh neem leaves in water at a rate of 12.5% w/w for 24 hours. The mixture was then sieved and sunflower oil added to improve adhesion. For the application of a mixture of neem-leaf extract and cow urine, cow urine was added. All applications of pesticides and biopesticides were done using knapsack sprayer at a rate of 198 litres per ha.

The experiment was arranged as split-split-plot in a randomised block design, where production systems (organic versus conventional) were the main plots with pest management as a sub-plot and nutrient management as a sub-sub plot. Treatments were replicated in three blocks, with a test plot size of 10 × 5 m as shown in Fig. 1. For organic treatments, a rotation was made in season 2 where organic plots were shifted to plots planted with sole legume in season 1, which is a

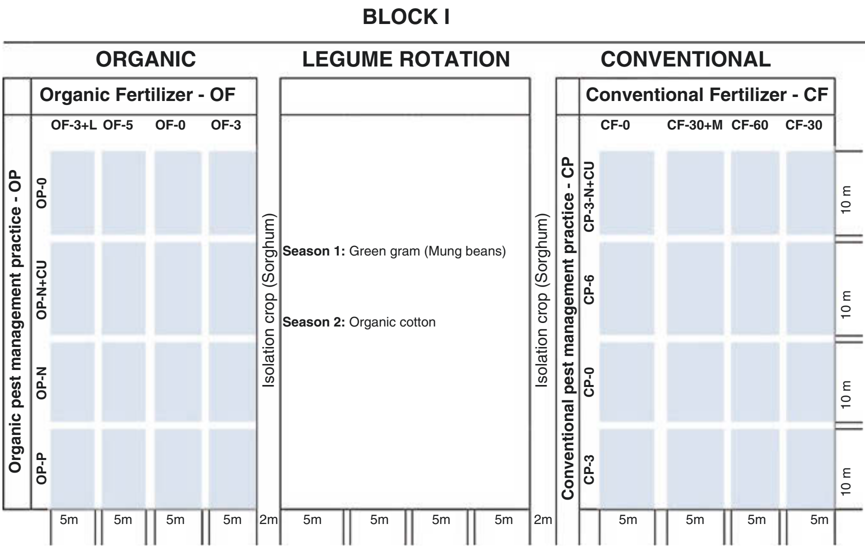

Fig. 1 Experimental plot layout (the abbreviations for the treatments are explained in Tables 2 and 3)

standard procedure for organic farmers in the area. Except for the innovative practices, the management of treatments followed the standard practices and recommended practices of farmers in the region. Organic and conventional plots were isolated by 2-m border rows planted with sorghum as indicated in Fig. 1.

2.5 Determination of Yield

Green gram yield was measured by harvesting the beans at the entire gross plot (10 × 5 m) during the third weeding. Cotton yield was measured by harvesting the net plot area (9 × 4 m) of each plot by hand picking, with the first round of harvesting done when approximately 60% of the cotton balls were open, which for seasons 1 and 2 was 142 and 135 days after sowing (DAS), respectively. A total of three rounds of harvesting cotton were conducted. The harvested green gram beans and seed cotton from each plot were weighed using a digital balance.

2.6 Assessment of the Profitability

We assess the economic performance of the analysed organic and conventional farming practices by the land rent, which is total revenues minus total production costs, except for the (opportunity) cost of the land. The total production costs include expenditures for purchased inputs and services as well as labour costs. The production costs were obtained by recording the costs of those inputs and activities that were done during the plot experiment and which would also be done by typical cotton producers in the area. These costs are similar to the costs that typical cotton producers in the area would have, whereas we assume that the opportunity costs of unpaid household labour are equal to the costs of hired labour for the same activity. Total revenue was calculated by multiplying the harvested quantities by the selling prices at the time of the harvest. The production costs and output prices that were used for calculating the land rents are presented in Tables 4 and 5, respectively. All costs and revenues were converted to US$ using an exchange rate of 2167.32 TZS US$$^{-1}$.

2.7 Statistical Analysis

Three different outcome variables were used in the statistical analysis: seed cotton yield (in Mg ha^{-1}), total revenue (in US$ ha^{-1}) and land rent (in US$ ha^{-1}). For each of these three outcome variables, the effects of the soil fertility treatments, the effects of the pesticide treatments and the effects of selected combinations of soil fertility and pesticide treatments were investigated. The selected combinations of soil fertility and pesticide treatments that were included in our analysis are conventional farming without fertilisation or pesticides (CF-0 & CP-0), currently practised conventional farming (CF-30 & CP-3), conventional farming with higher fertilisation and pesticide application rates (CF-60 & CP-6), innovative conventional farming practices (CF-30 + M & CP-3-N + CU), organic farming without fertilisation or pesticides (OF-0 & OP-0), currently practised organic farming (OF-3 & OP-P), organic farming with higher fertilisation rate (OF-5 & OP-P) and innovative organic farming practices (OF-3 + L & OP-N + CU). As the conventional and organic no-input treatments (CF-0 & CP-0 and OF-0 & OP-0) were identical in the first season but different in the second season (due to different pre-crops), the statistical analysis of the selected combinations of treatments considered these two treatments as the same treatment in season 1 but as two different treatments in season 2.

In order to investigate the effect of the soil fertility and pesticide treatments, we used the ordinary least squares (OLS) method to test effects on each of the three outcome variables using the soil fertility treatments, the pesticide treatments, the interaction terms between the soil fertility treatments and the pesticide treatments, and the block in which the plot was located as explanatory variables. We calculated the least squares mean values for each soil fertility and pesticide treatment (Searle et al. 1980) and conducted pairwise tests of equal means, where we present the results of these tests as "compact letter display" (Piepho 2004). We investigated the effects of the selected combinations of soil fertility and pesticide treatments in a similar way, but we used only the selected combinations of treatments and the block in which the plot was located as explanatory variables.

All calculations and statistical analyses were conducted with the statistical software "R" (R Core Team 2019) using the add-on packages "emmeans" (Lenth 2019), "multcomp" (Hothorn et al. 2008) and "ggplot2" (Wickham 2016).

Table 4 Production costs (in growing season 2015/16 and 2016/17)

Description	Treatments	Unit	Costs
Labour, oxen and plough for land preparation	All	US\$ ha^{-1}	34.20
Manure 3 Mg ha^{-1} (10,000 TZS Mg^{-1})	CF-30 + M, OF-3, OF-3 + L	US\$ ha^{-1}	13.84
Manure 5 Mg ha^{-1} (10,000 TZS Mg^{-1})	OF-5	US\$ ha^{-1}	23.07
Labour for manure application 3 Mg ha^{-1}	CF-30 + M, OF-3, OF-3 + L	US\$ ha^{-1}	3.42
Labour for manure application 5 Mg ha^{-1}	OF-5	US\$ ha^{-1}	5.70
Labour for land pulverisation/harrowing	All	US\$ ha^{-1}	17.10
Cotton seed	All	US\$ ha^{-1}	7.98
Labour for cotton sowing	All	US\$ ha^{-1}	22.80
Green gram seed	OF-3 + L	US\$ ha^{-1}	11.97
Labour for green gram sowing	OF-3 + L	US\$ ha^{-1}	17.10
DAP at planting (75 kg ha^{-1}, 1200 TZS kg^{-1})	CF-30	US\$ ha^{-1}	41.53
DAP at planting (100 kg ha^{-1}, 1200 TZS kg^{-1})	CF-60	US\$ ha^{-1}	55.37
Labour for DAP application at planting	CF-30, CF-60	US\$ ha^{-1}	17.10
Urea as top-dress (35.9 kg ha^{-1}, 1200 TZS kg^{-1})	CF-30	US\$ ha^{-1}	19.86
Urea as top-dress (91.4 kg ha^{-1}, 1200 TZS kg^{-1})	CF-60	US\$ ha^{-1}	50.61
Urea as top-dress (65.2 kg ha^{-1}, 1200 TZS kg^{-1})	CF-30 + M	US\$ ha^{-1}	36.11
Labour for urea application as top-dress	CF-30, CF-60, CF-30 + M	US\$ ha^{-1}	17.10
Labour for first weeding	All	US\$ ha^{-1}	22.80
Labour for second weeding	All	US\$ ha^{-1}	20.52
Labour for third weeding	All	US\$ ha^{-1}	15.96
Ninja (3 applications: 2000 TZS (150 ml)$^{-1}$)	CP-3	US\$ ha^{-1}	6.84
Ninja (6 applications: 2000 TZS (150 ml)$^{-1}$)	CP-6	US\$ ha^{-1}	13.68

(continued)

Table 4 (continued)

Description	Treatments	Unit	Costs
Natural Pyrethrin extract (1 application: 3500 TZS (110 ml)$^{-1}$)	OP-P	US$ ha^{-1}	3.99
Neem leaves for biopesticide	CP-3-N + CU, OP-N, OP-N + CU	US$ ha^{-1}	0.00
Sunflower oil for biopesticide (1 application: 3.5 l ha^{-1}, 2500 TZS l^{-1})	OP-N, OP-N + CU	US$ ha^{-1}	3.99
Sunflower oil for biopesticide (3 applications: 10.4 l ha^{-1}, 2500 TZS l^{-1})	CP-3-N + CU	US$ ha^{-1}	11.97
Cow urine for biopesticide (1 application: 4.94 l ha^{-1}, 500 TZS l^{-1})	OP-N + CU	US$ ha^{-1}	1.14
Cow urine for biopesticide (3 applications: 14.83 l ha^{-1}, 500 TZS l^{-1})	CP-3-N + CU	US$ ha^{-1}	3.42
Labour for scouting for pests	OP-P, OP-N, OP-N + CU	US$ ha^{-1}	10.26
Labour for preparation of biopesticide (1 application)	OP-N, OP-N + CU	US$ ha^{-1}	5.70
Labour for preparation of biopesticide (3 applications)	CP-3-N + CU	US$ ha^{-1}	17.10
Labour for 1 application of (bio-)pesticides	OP-P, OP-N, OP-N + CU	US$ ha^{-1}	4.56
Labour for 3 applications of (bio-)pesticides	CP-3, CP-3-N + CU	US$ ha^{-1}	13.68
Labour for 6 applications of (bio-)pesticides	CP-6	US$ ha^{-1}	27.36
Bags for harvested cotton	All	US$ ha^{-1}	11.40
Labour for green gram harvesting	OF-3 + L	US$ ha^{-1}	5.70
Labour for cotton harvesting	All	US$ kg^{-1}	0.0277
Labour and vehicle for transport of cotton to selling point	All	US$ ha^{-1}	5.70

Note: The abbreviations of the treatments are explained in Tables 2 and 3
Source: own recording of production costs, information obtained from experts, own calculations

Table 5 Output prices (at the end of growing season 2015/16 and 2016/17)

Output	Unit	Price
Cotton, conventional	US$ kg^{-1}	0.461
Cotton, organic	US$ kg^{-1}	0.554
Green gram	US$ kg^{-1}	0.646

Source: observations at cotton selling points and local markets

3 Results

3.1 Weather Conditions in the Growing Seasons

The total rainfall recorded in the cotton growing season 1 (November 2015 to June 2016) was 759 mm, while that in season 2 (October 2016 to June 2017) was 522 mm (Table 6). The rainfall recorded in season 1 was above the long-term (1994–2011) annual rainfall mean of 668 mm (Kabote et al. 2013), while the rainfall in season 2 was below average.

The mean daily soil and air temperatures for seasons 1 and 2 were rather similar (Fig. 2). There was slightly higher mean solar radiation in season 2 (226 W m^{-2}) than in season 1 (211 W m^{-2}) and less soil moisture in season 2 than in season 1.

3.2 Yield and Economic Performance

The results regarding the yield and economic performance are summarised in Table 7, whereas the most important results are visualised in Figs. 3, 4 and 5. The weather conditions in the study area in season 1 (2015/16) were well suited for cotton production and resulted in relatively high cotton yields and a high profitability of cotton production. In season 2, however, moisture stress at the end of the growing season resulted in low yields and very poor economic performance.

The seed cotton yields in the two respective seasons in the currently practised low-input conventional (CF-30 & CP-3: 1.27 and 0.37 Mg ha^{-1}) and organic (OF-3 & OP-P: 1.37 and 0.63 Mg ha^{-1}) farming were not significantly different. However, the low-input organic practice had a higher land rent (LR) (524 and 139 US$ ha^{-1}) than the low-input conventional practice (278 and −114 US$ ha^{-1}) in both seasons. Higher-input conventional farming had a significantly higher cotton yield (CF-60 &

Table 6 Summary of mean daily values for weather parameters at the experiment site for the two cotton growing seasons (Nov 2015 to Jun 2016, Oct 2016 to Jun 2017)

Season		RH (%)	Temp (°C)	Precipitation (mm)	Solar radiation (W m^{-2})	Soil VWC (m^3 m^{-3})	Soil WFPS (%)	Soil temp (°C)
1	Mean	71	23.8		247	0.11	32.4	28.0
	Min	23	20.7	0	211	0.05	15.3	23.8
	Max	103	27.4	45	339	0.18	51.3	31.5
	Total			759				
2	Mean	54	24.6		259	0.11	32.7	29.4
	Min	39	20.4	0	226	0.05	13.8	22.6
	Max	75	28.5	48	438	0.21	63.0	35.5
	Total			522				

RH Relative humidity, *VWC* volumetric water content, *WFPS* water-filled pore space

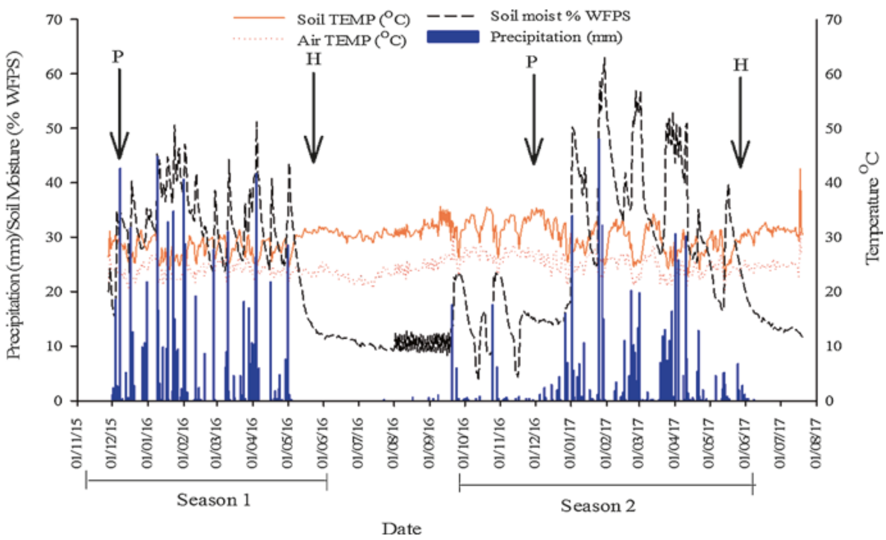

Fig. 2 Variation in rainfall, soil moisture (% water-filled pore space, WFPS) and soil and air temperature during the experiment period for season 1 (Nov 2015 to June 2016) and season 2 (Oct 2016 to June 2017). *Note: Arrows show planting (P) and harvesting (H) time*

CP-6: 1.76 and 0.50 Mg ha^{-1}) than higher-input organic farming (OF-5 & OP-P: 1.36 and 0.46 Mg ha^{-1}) in season 1, but the difference is insignificant for season 2, while the differences in the land rent between the higher-input conventional (422 and −121 US$ ha^{-1}) and organic (509 and 36 US$ ha^{-1}) practices are statistically insignificant for both seasons. The innovative conventional practice (CF-30 + M & CP-3-N + CU: 1.69 and 0.47 Mg ha^{-1}) had a significantly higher yield in season 1 than the innovative organic practice (OF-3 + L & OP-N + CU: 1.32 and 0.66 Mg ha^{-1}), but the difference is statistically insignificant for season 2. However, the innovative conventional practice (460 and −69 US$ ha^{-1}) had a statistically significantly lower land rent than the innovative organic practice (615 and 227 US$ ha^{-1}) both in seasons 1 and 2.

The highest seed cotton yields in season 1 were obtained in the higher-input conventional farming practice (CF-60 & CP-6: 1.76 Mg ha^{-1}) and the innovative conventional farming practice (CF-30 + M & CP-3-N + CU: 1.69 Mg ha^{-1}), whereas there are no statistically significant differences in the seed cotton yields between any of the treatments in season 2.

Given that organic cotton farming requires lower production costs and receives a higher output price than conventional cotton farming, it generally generates notably higher land rents than conventional cotton farming in spite of similar or lower seed cotton yields. Particularly the innovative organic practice (OF-3 + L & OP-N + CU: 615 and 227 US$ ha-1) generates the highest land rent both in seasons 1 and 2, and these land rents are significantly higher than the land rents of all conventional treatments.

Table 7 Least squares means of production costs, cotton yields, total revenue and land rents for different treatments in two growing seasons

Treatment	Costs (US$ ha^{-1})		Cotton yield (Mg ha^{-1})				Total revenue (US$ ha^{-1})				Land rent (US$ ha^{-1})			
Season	S1	S2	S1		S2		S1		S2		S1		S2	
	Fertility management practices													
CF-0	219	198	1.23	ab	0.45	a	566	a	208	a	347	a	10	bcd
CF-30	320	293	1.39	bc	0.43	a	643	ab	200	a	324	a	−-93	ab
CF-60	369	339	1.56	c	0.50	a	722	bc	230	a	353	a	−109	a
CF-30 + M	298	269	1.52	c	0.49	a	701	bc	226	a	403	ab	−43	abc
OF-0	209	189	1.19	a	0.48	a	657	ab	268	a	448	b	79	de
OF-3	232	205	1.42	c	0.44	a	789	c	242	a	556	c	37	cd
OF-5	237	215	1.17	a	0.38	a	651	ab	212	a	414	ab	−3	abcd
OF-3 + L	266	242	1.39	bc	0.50	a	930	d	396	b	664	d	155	e
	Pesticide management practices													
CP-0	269	248	1.22	a	0.48	a	564	a	222	ab	295	a	−27	ab
CP-3	294	267	1.39	abc	0.40	a	640	ab	183	a	346	ab	−83	a
CP-6	319	290	1.53	bc	0.49	a	708	bc	224	ab	389	bc	−65	a
CP-3-N + CU	324	295	1.56	c	0.51	a	720	bc	235	ab	396	bc	−60	a
OP-0	219	195	1.29	a	0.44	a	747	c	280	ab	528	d	84	c
OP-P	239	217	1.36	ab	0.53	a	802	c	322	b	562	d	106	c
OP-N	241	218	1.22	a	0.38	a	716	bc	241	ab	474	cd	23	abc
OP-N + CU	245	221	1.31	a	0.45	a	762	c	275	ab	518	d	54	bc
	Selected combinations of fertility and pesticide management practices													
CF-0 & CP-0	188	171	1.08	a	0.44	a	545	a	203	a	357	ab	32	abc
CF-30 & CP-3	310	285	1.27	ab	0.37	a	588	a	171	a	278	a	−114	a
CF-60 & CP-6	388	354	1.76	c	0.50	a	810	b	232	Aab	422	abc	−121	a

CF-30 + M & CP-3-N + CU	322	288	1.69	c	0.47	a	782	b	219	ab	460	bc	−69	ab
OF-0 & OP-0	188	172	1.08	a	0.47	a	545	a	261	ab	357	ab	90	abc
OF-3 & OP-P	232	212	1.37	b	0.63	a	756	b	351	ab	524	cd	139	bc
OF-5 & OP-P	244	219	1.36	ab	0.46	a	752	b	255	ab	509	cd	36	abc
OF-3 + L & OP-N + CU	273	254	1.32	ab	0.66	a	888	b	481	b	615	d	227	c

Notes: S1 = growing season 2015/16, S2 = growing season 2016/17. The letters on the right-hand side of the mean values present the results of pairwise tests for equal means, where mean values in the same column and in the same panel of the table that have the same letter are not statistically significantly different at a significance level of 5%. The abbreviations of the treatments are explained in Tables 2 and 3

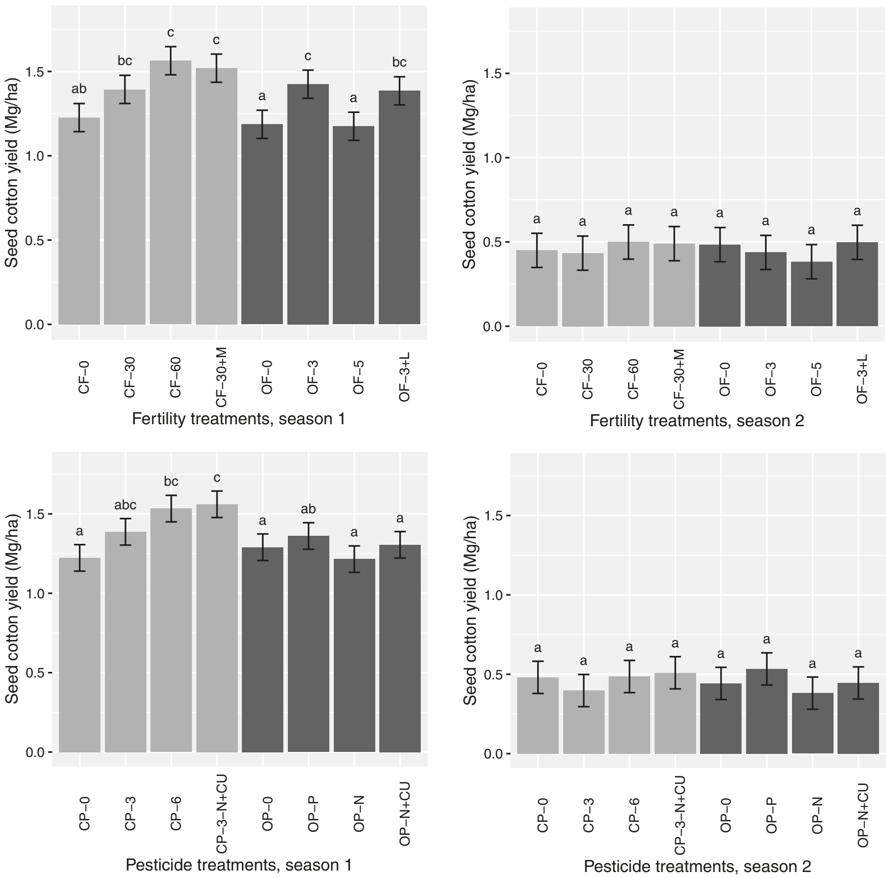

Fig. 3 Effect of conventional and organic fertility and pesticide treatments on seed cotton yields in growing seasons 1 (2015/16) and 2 (2016/17). *The bars indicate the least-squares means, while the vertical lines indicate the 95% confidence intervals of these mean values. The abbreviations of the treatments are explained in* Tables 2 and 3

3.3 *Yield Compared to Potential Yield*

The seed cotton yield ranged from 1.19 to 1.42 Mg ha^{-1} for organic farming practices and from 1.22 to 1.56 Mg ha^{-1} for conventional farming practices in season 1 (Table 7). For season 2, the yields ranged from 0.40 to 0.51 Mg ha^{-1} for conventional and from 0.38 to 0.52 Mg ha^{-1} for organic practices. As Fig. 3 indicates, both fertility and pest management practices had statistically significant effects on the seed cotton yield in season 1. However, in season 2, neither fertility management

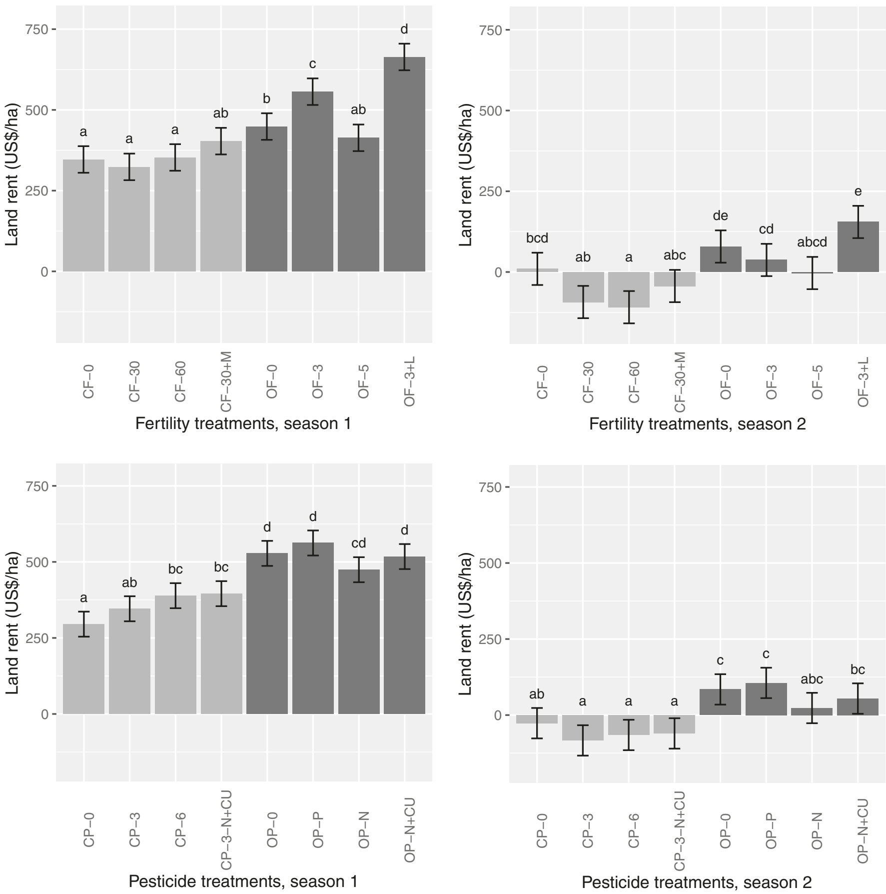

Fig. 4 Effect of conventional and organic fertility and pesticide treatments on the land rent in growing seasons 1 (2015/16) and 2 (2016/17). *The bars indicate the least-squares means, while the vertical lines indicate the 95% confidence intervals of these mean values. The abbreviations of the treatments are explained in* Tables 2 and 3

nor pest management practices had a significant effect on cotton yield. The yields observed in this study were considerably lower than the potential yield of the test variety (UK MO8) of 2.5 Mg ha^{-1} (Lukonge et al. 2007) for both seasons. For season 1, the yield was 52% to 43% below the potential yield in the organic system and 51% to 40% below the potential yield in the conventional system. For season 2, the yield was 84% to 80% and 85% to 79% below the potential yield in the organic and conventional system, respectively.

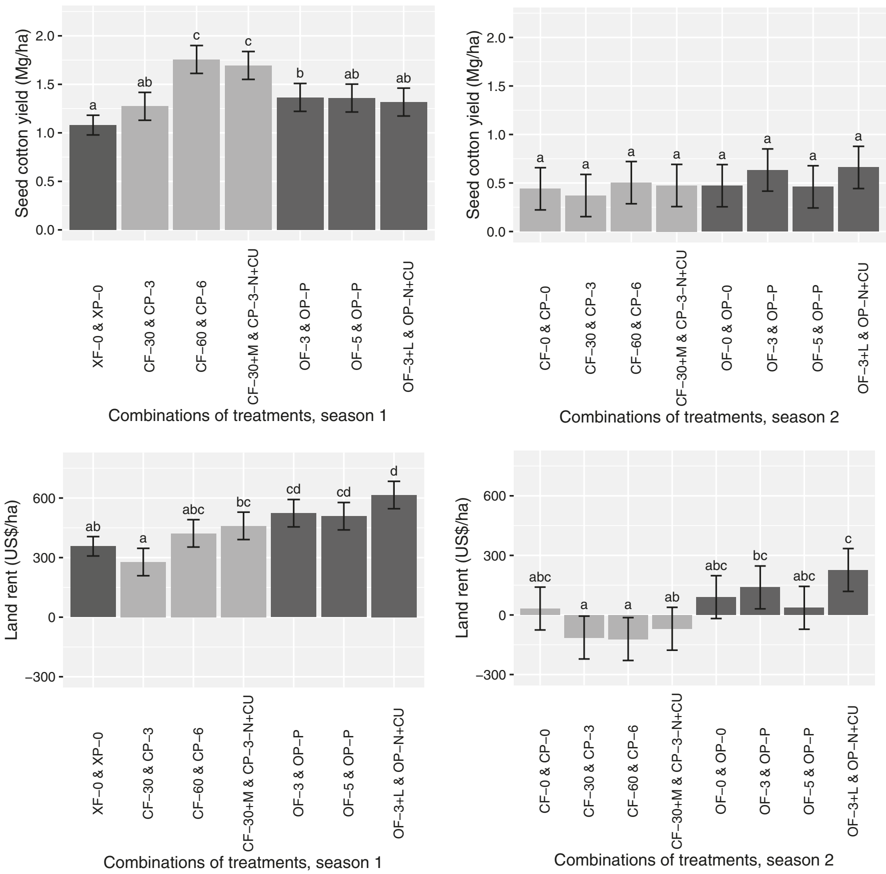

Fig. 5 Effects of selected combinations of fertility and pesticide treatments on the cotton yield and the land rent in growing seasons 1 (2015/16) and 2 (2016/17). *The bars indicate the least-squares means, while the vertical lines indicate the 95% confidence intervals of these mean values. The abbreviations of the treatments are explained in* Tables 2 and 3, *whereas treatment "XF-0 & XP-0" indicates treatments "CF-0 & CP-0" and "OF-0 & OP-0"*

4 Discussion

4.1 Yield and Economic Performance

Current Practices

The similarity of cotton yields between current organic and conventional practices can be linked to the fact that the current input levels in organic and conventional cotton farming are rather similar. For instance, the N input in the currently practised conventional fertilisation treatment (30 kg N ha^{-1}) is similar to the N input from 3 Mg ha^{-1} FYM in the currently practised organic fertilisation treatment (30.9 kg N ha^{-1}, given an N content of 1.03% in the applied FYM). This result aligns with Cavigelli et al.

(2009) who found that wheat yield was similar in organic and conventional systems. However, such comparisons are likely to be highly dependent on soil and climate conditions. Therefore, many studies indicate lower yields in organic than in conventional farming (e.g. Forster et al. 2013; Lee et al. 2015; Ponisio et al. 2015; Kniss et al. 2016; Suja et al. 2017; de Ponti et al. 2012; Seufert et al. 2012). These studies were done in high-input farming systems under suitable climatic conditions with high fertiliser levels in conventional farming. Our result of a better economic performance of organic production compared to conventional production is linked to the lower input costs, especially the use of manure instead of inorganic fertilisers, and a higher price of organic cotton compared to conventional cotton.

Higher-Input Scenario

For the higher-input scenarios, the higher yield of conventional farming compared to organic farming in season 1 is mainly an effect of the higher rainfall in this season, which favours higher N input in conventional (60 kg N ha^{-1}) than in organic farming (51.5 kg N ha^{-1}), and more effective pest management in the conventional treatments than in the organic treatments. The higher input of FYM in organic farming (OF-5) resulted in a significant reduction in crop yield, for which the reason is not known. An increase in N input in cotton farming increases seed cotton yield (Bell et al. 2003; Prasad and Siddique 2004) because the increased N rate increases the leaf photosynthetic rate (Cadena and Cothren 1995). This leads to higher boll weight and seed cotton yield. This result is in line with most studies which show higher yields in conventional than in organic systems (Seufert et al. 2012). For instance, Forster et al. (2013) found in a cotton-wheat-soybean rotation in India a higher yield in a conventional treatment receiving 105 kg N ha^{-1} than in an organic treatment receiving 65 kg N ha^{-1}.

In season 2, yields were considerably lower with no significant differences in yields between the two systems and treatments. This is linked to low soil moisture availability in season 2 (the rainfall received in season 2 was 26% less than in season 1), such that soil moisture was the most limiting factor that resulted in stunted plants which were then unable to utilise the higher N input. Due to lower production costs and a higher cotton price of organic cotton compared to conventional cotton, higher-input organic farming (OF-5 & OP-P) had a somewhat better economic performance than higher-input conventional farming (CF-60 & CP-6), but these differences are statistically insignificant in both growing seasons.

Innovative Practices

Manure-Fertiliser Combination

The innovative conventional practice of applying FYM in addition to the currently practised rate of inorganic fertilisers (CF-30 + M) gives a similar yield as the higher-input conventional fertility treatment (CF-60), which is likely caused by similar N inputs in these two treatments (CF-60: 60 kg N ha^{-1}; CF-30 + M: 60.9 kg N ha^{-1}).

The innovative conventional practice of applying FYM gives a slightly higher yield than the currently practised fertilisation with inorganic fertilisers only (CF-30), but this (small) difference in the yield is statistically insignificant. Hence, in contrast to many existing studies (e.g. Khaliq et al. 2006; Hulihalli and Patil 2008; Kumari et al. 2010; Anwar-ul-Haq et al. 2014; Moe et al. 2017; Rao et al. 2017), we do not find that combining inorganic fertilisers with manure gives significantly higher yields than applying inorganic fertilisers alone. For instance, Rao et al. (2017) find a significant synergistic interaction effect between FYM and inorganic fertilisers and argue that FYM acts as a source of additional nutrients and supports moisture retention. Kumari et al. (2010) argue that FYM increases microbial activity and, hence, nutrient availability to cotton plants. Moe et al. (2017) argue that combining inorganic fertilisers with manure results in higher yields due to continuous supply of nutrients throughout the growing season, given that inorganic fertilisers release nutrients rapidly during the early growth stages followed by gradual release of nutrients from organic manure at a later stage.

The economic performance of the innovative conventional fertility treatment is slightly better than the economic performance of the current practice and the higher-input fertility treatment, but these differences are statistically insignificant. This is in contrast to results from other studies which indicate significantly higher economic performance of combining inorganic fertilisers and manure than applying inorganic fertilisers alone. For instance, Anwar-ul-Haq et al. (2014) report higher yield and economic performance of cotton from combining 20 Mg ha^{-1} manure and NPK (at 88 kg N ha^{-1}) than sole NPK application (at 175 kg N ha^{-1}), which are very high application rates compared to those of this study (3 Mg ha^{-1} manure, 30 or 60 kg N ha^{-1} from inorganic fertilisers).

Three Sprays of Neem-Leaf Extract and Cow Urine

Spraying three times with neem-leaf extract in combination with cow urine has a similar effectiveness as spraying six times with a conventional pesticide containing lambda-cyhalothrin and likely has a slightly higher effectiveness than spraying three times with a conventional pesticide containing lambda-cyhalothrin, but this difference is statistically insignificant. The leaves of the neem tree (*Azadirachta indica)* contain biologically active components, and their potency is increased when mixed with cow urine (Gupta 2005). The biologically active components in the neem-leaf extract act broadly as toxicant, repellent, anti-feedant and growth-disrupting substances on insect pests (Gujar 1992) and also act as powerful insect growth regulators (IGR) (Subbalakshmi et al. 2012). The combinations of cow urine and neem-based products have shown significant synergistic effects to enhance product toxicity resulting in pest mortality (Gahukar 2013) but are safe to insect predators, particularly beetles (Gupta 2005). The land rent when spraying three times with neem-leaf extract and cow urine is similar to the one of spraying six times with a conventional pesticide and may be slightly higher than the land rent when spraying three times with a conventional pesticide.

Cotton-Legume Intercrop

In spite of potential competition for soil moisture and light between the cotton plants and the green gram plants, the cotton yield in the cotton-legume intercrop was similar to the cotton yield of the currently practised organic fertility practice, which applied the same amount of FYM but had no intercropping. Hence, our results contradict the results of several other studies that report lower cotton yields in cotton-legume intercropping (e.g. Khan and Khaliq 2004; Nandini and Chellamuthu 2004; Reddy and Shaik 2009; Hallikeri et al. 2007; Mankar and Nawlakhe 2009; Sankaranarayanan et al. 2012; Khargkharate et al. 2014; Jayakumar and Surendran 2017; Singh et al. 2017). For instance, Jayakumar and Surendran (2017) associate the lower cotton yields of intercrops with the early, vigorous growth of the intercrop that result in a smothering effect on the cotton crop. Similarly, Singh et al. (2017) report a significant reduction in seed cotton yield in cotton-mung bean and cotton-cowpea intercrop as compared to sole cotton. The higher yield of the intercrop in our case may be due to beneficial effects of the legume intercrop on soil fertility and nitrogen supply (Thilakarathna et al. 2016). Given the rather high cotton yield in the intercrop and the additional revenue from green gram production, cotton-green gram intercropping gives the highest land rent of all fertility treatments in both seasons. This result is in line with results reported by Jayakumar and Surendran (2017) and Singh et al. (2017) who also reported higher economic performance of cotton-legume intercrop compared to cotton without intercrop.

4.2 Yield as Compared to Potential Yield

The lower yield compared to the potential yield of the cotton variety UK MO8 in seasons 1 and 2 in this study for all treatments and their combinations is linked to the low rainfall in season 2 and soil fertility limitations. Low rainfall in season 2 severely affected the yield and, hence, masked the effects of the fertility and pesticide treatments. The rainfall in season 2 (522 mm) was on the lower side of the minimum water required for cotton growth (500 mm) (OECD 2008). With the same level of nutrient and pest management in the two seasons, soil moisture was the major limiting factor to primary productivity and biomass production. A series of intra-season dry spells were experienced in both seasons due to intermittent rain events (Fig. 2). The cotton yield in season 1 was higher than the cotton yield in season 2 but still 36% less than the potential yield of UK MO8, which is narrower than the average yield gap of 43% for cotton in semi-arid Africa as reported by Hengsdijk and Langeveld (2009). A similar study in India reported lower than potential yield in cotton in one season with poor growing conditions due to low rainfall and waterlogging in the conventional but not in the organic system (Forster et al. 2013). Hengsdijk and Langeveld (2009) show that water is the main contributor to the yield gap of up to 30% in semi-arid Africa regions to various crops including cotton, and they reported an average actual yield of 2.0 vs. a potential yield of 3.3 Mg ha^{-1}. The soil properties in the study area affecting soil fertility, including high soil pH, might also have reduced cotton yield. As indicated in Bwana (2019), the soil was classified as marginally suitable for cotton production due to soil limitations.

5 Conclusions and Recommendations

Notwithstanding the different results between the two seasons, we conclude that for the current cotton farming practices, there is no significant difference in the seed cotton yields between smallholder organic and conventional production practices. A difference would only occur under good rainfall conditions if the rate of nitrogen fertilisation is increased to 60 kg N ha^{-1} or more in the conventional farming system. Application of manure in combination with a low rate of inorganic nitrogen fertilisers had a similar effect on the yield than applying a higher rate of inorganic fertilisers. Applying neem-leaf extract and cow urine as pesticide gives a similar yield and land rent as applying pyrethrum (in organic farming) or as applying a high rate of a synthetic pesticide (in conventional farming). Under conditions of limited rainfall as in the second growing season of our experiment, moisture stress becomes limiting, and hence, fertility and pest management practices have no significant effects on the yield. Under the prevailing semi-arid conditions, smallholder farmers are rational to apply only low rates of fertilisers and pesticides.

Based on our study, we conclude that smallholder farmers in our study region can improve their economic situation by intercropping cotton with grain legumes and applying neem-leaf extract and cow urine for pest management. Within the bounds of farming practices currently practised in the study area, our results also indicate that individual farmers with interest in organic production methods could economically benefit by adopting organic cotton production. Further research could investigate various agronomic, environmental and economic aspects of cotton-legume intercropping (e.g. effects of different legume species) and of using neem-leaf extract and cow urine as biopesticide.

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