Impacts of Land Use Cover Change, Cropland Expansion and Climate Change on the Potential of Yield and Production in Ethiopia, Gambella Region

Azeb W. Degife

München 2020

Dedication

This thesis is dedicated to the memory of my mother Askale Mulugeta, a smart woman who I still miss every day. You taught me everything except how to live without you. I was never ready for you to leave. Losing you is a permanent and inexpressible wound that will never quite heal. Now I know why you always wanted me to be strong… because you knew that, one day, I would need the strength to bear your loss. Not having you by my side is the pain I will suffer the rest of my life. I love you and I miss you so much Akeye yene dege enate…

Your,

Medamcha

Impacts of Land Use Cover Change, Cropland Expansion and Climate Change on the Potential of Yield and Production in Ethiopia, Gambella Region

Azeb W. Degife

Dissertation
an der Fakultät für Geowissenschaften
der Ludwig-Maximilians-Universität
München

vorgelegt von
Azeb W. Degife
aus Äthiopien

München, den 16.01.2020

Erstgutachter:	Prof. Dr. Wolfram Mauser
Zweitgutachter:	Dr. Florian Zabel
Tag der mündlichen Prüfung:	27.02.2020

1. Summary

The Ethiopian Constitution asserts state ownership of land. There are no private property rights in land – it is the common property of the people of Ethiopia; however, the state may allocate small plots of land to farmers. Since the 1990s, the government has formulated a long-term economic development strategy called Agriculture Development Led Industrialization (ADLI), which is its overarching policy response to Ethiopia's food security and agricultural productivity challenge. The strategy focuses primarily on the expansion of large-scale commercial farms and improved productivity in smallholdings.

The Ethiopian government identified Gambella region as one of the regions in Ethiopia suitable for agricultural investments, and classified most parts of the area as under-utilized, having a huge potential for agriculture production. However, the unintegrated plan on large-scale land acquisition has caused tremendous environmental devastation in the region, including deforestation, biodiversity depletion, and the draining of wetlands. There are several issues that need to be addressed in depth for a future, sustainable development. This thesis, however, will focus mainly on three aspects: (1) examining the rate, extent and distribution of various land-use land-cover changes (LULCC) in Gambella Regional State and looking at the expansion of farmland and different farming intensities in the region; (2) estimating the magnitude and extent of the intensification potential of the key Gambella cereal crops (maize and sorghum) and seeking to identify potential cropland expansion areas in the region; and (3) investigating the impacts of future climate change on potential crop yields, with maize as an exemplar, under climate change scenarios in Gambella, Ethiopia.

1) In the last three decades (1987–2017), the rate, extent and distribution of various LULCC in Gambella has depended on three main factors: resettlement, population growth and increasing agricultural land pressure. All three factors contribute to LULCC in the region. An LULCC analysis was conducted, based on Landsat 5 and Sentinel 2A satellite images and fieldwork. The results show that farmland decreased by 26km^2 from 1987–2000; however, during the last two decades, agricultural land area increased by 599km^2, mainly at the cost of tropical grasslands and forests. The results also show that tropical grasslands declined by 17.76% from 1987–2017. Gambella National Park, which is the nation's largest national park and ecosystem, was also affected by cropland expansion.

2) Over the past few decades, population growth has aggravated rapid agricultural land expansion and intensification in the region. As a result, the Ethiopian government has used agricultural intensification and cropland expansion as the key policies to increase food production in Ethiopia. Although Gambella is one of the regions in Ethiopia that is highly suitable for agriculture, the local people still face food shortages. Thus, to understand the potential food production of the region, the biophysical process-based model PROMET (Process of Radiation Mass and Energy Transfer) was run for the Gambella region on both the actual and all potentially suitable cropland for six selected scenarios (different degrees of intensification, ranging from low-input rainfed to high-input irrigated agriculture and degrees of expansion, considering the best 30% or 50% of land to be utilized for expansion) for the period 1997–2017, with a spatial raster grid of 30 arc seconds (approx. 940 × 940m)

resolution, to provide information on potential crop yields. Land-use scenarios of agricultural intensification and expansion results reveal that Gambella could serve as a bread basket for the entire country, which could improve national food production. The potential calorie production in the potential area of the region by far exceeds the current and possible future caloric requirements of Gambella's population. For instance, for the top 50% expansion scenario, calorie production increased by +428% for the low input scenario and by +1,092% for the high-input scenario, compared to the reference calorie crop production of the region. By assuming a daily diet of 2,200 kcal/cap/day, Gambella region's calorie production in high-input scenarios could nourish up to 21 million people, thus improving national food production.

3) Unintegrated large-scale agricultural investment, inappropriate cropland expansion, poor intensification and changing climate conditions have caused tremendous impacts on agricultural production. In the region, temperature increase, changing soil water availability and atmospheric CO_2 concentration have different effects on the simulated yield potential, and the results demonstrate that the dominance of heat response under future climate conditions is contributing to 85% of changes in total yields. For the Gambella region, on today's cropland and to the best (in terms of highest potential yields) 50% expansion area, under rainfed and irrigated conditions, climate change impacts on yields until 2100 for Representative Concentration Pathways (RCPs) 2.6, 4.5, and 8.5 from a climate model ensemble show that rainfed yields will decrease by 15% and 14% respectively for RCPs 2.6 and 4.5, and that yields will decrease by up to 32% under RCP 8.5. Irrigated maize yield decreases by 4.3%, 23.0% and 44.5% under RCPs 2.6, 4.5 and 8.5, respectively, for same period. While higher temperature determines the phenological progress of crops and decreases the growing period of maize by up to 23 days under rainfed agriculture, temperature stress also reduces the rate of photosynthesis. We show that temperature stress is mainly responsible for yield reduction under future climate conditions in the Gambella region. Therefore, new varieties with higher growing degree days are primarily required for the region in order to adapt to future climate conditions.

To sum up, the thesis shows the intricacies between LULCC, potential yield production and future impact of climate change on the potential food production in the region. Gambella region is still far away from a terminal stage of human interference. This opens up the chances to develop and implement policies to ensure the sustainable future agriculture development of the region.

2. Acknowledgements

First and foremost, I offer my sincerest gratitude to the almighty God for showering me with all the blessings.

I express my sincere and deepest gratitude to my supervisor, Prof. Dr Wolfram Mauser, Chair of Physical Geography and Remote Sensing at the Department of Geography at the Ludwig-Maximilians-Universität München, who has supported me throughout my thesis with his patience and knowledge. His office was always open whenever I ran into a spot of trouble or had a question about my research or writing. He consistently allowed this paper to be my own work, but steered me in the right the direction whenever he thought I needed it.

I would also like to acknowledge Dr Florian Zable the second supervisor of this thesis, and I am gratefully indebted for his very valuable comments on it.

I extend my thanks to the Ethiopian Investment Commission and Gambella Regional State Investment Office.

I am highly thankful to Physical Geography and Remote Sensing at the Department of Geography at Ludwig-Maximilians-Universität München and to the Rachel Carson Center (RCC) for Environment and Society for covering my conference fees and fieldwork expenses.

I would like to thank all my officemates and the staff members at Physical Geography and Remote Sensing at the Department of Geography at Ludwig-Maximilians-Universität München for the valuable discussions, kind support and vibey atmosphere.

I must express my very profound gratitude to my dear dad Worku Degife, you have been an inspiration throughout my life. You always supported my dreams and aspirations, and if I do say so myself, I think you did a great job raising me. I would like to thank you for all you do, and all you have done for me. I love you.

I feel a deep sense of gratitude to my late mom Askale Mulugeta, who formed part of my vision and taught me the good things that really matter in life. The happy memory of my mom still provides persistent inspiration for my journey in this life.

I feel a deep sense of gratitude to my hubby Bisrat Assefa (Bisrity), for providing me with unfailing support and continuous encouragement throughout my years of study and through the process of researching and writing this thesis. Thanks is not enough to balance out what you have done for me. I am proud to be your wife. You are the best. I am truly blessed to have you in my life. I love you!

YeGabriel and Noah, my little angels – both of you have been the light of my life and have given me the extra strength and motivation to get things done. I love you so much more than you can even imagine.

All my family and friends, especially Mike, Yohannes, Emawayshi, Meserat, Serkalem, Bezuye, Abebe, Boge, Seble, Truiwork, Yabsera, Seblewongel, Tade and Samson for supporting me throughout all my studies – I thank you.

Finally, very special gratitude goes to Deutscher Akademischer Austauschdienst (DAAD) for helping and providing the funding over the last four years, allowing me to finish my studies successfully.

Azeb W. Degife

3. Table of Contents

4. List of Figures

5. Introduction

5.1 Agricultural activities in the Gambella Region, Ethiopia

The Ethiopian economy is among the most vulnerable in sub-Saharan Africa (IMF 2016). It is heavily dependent on the agricultural sector, which has suffered from recurrent droughts and extreme fluctuations of output (Kahiluoto and Rötter 2009, Tilahun 2014). Agricultural production, for instance, had been growing by about 2.3% during 1980–2000 while the population was growing on average at a rate of 2.9% per year, leading to a decline in per capita agricultural production by about 0.6% per year (Demeke, Guta et al. 2004). As a result, domestic food production has failed to meet the food requirements of the country. The number of food insecure households in Ethiopia has been increasing since the 1960s (Demeke, Guta et al. 2006) and the annual food deficit increased from about 0.75 million tons in 1979–80 to 1.4 million tons in 2000 (Demeke, Guta et al. 2004). Since 1994, the federal government adopted an Agricultural Development Led Industrialization (ADLI) strategy (Girmay 2015). The main goal of the strategy was to achieve accelerated economic development, particularly in the agricultural sector, and to make the sector a springboard for the development of other domains of economic activity (Fenta 2014, Girmay 2015). Thus, the Ethiopian government identified Gambella region as a major target point for agricultural investment (Gebresenbet 2016).

Gambella is located in the south-western part of the country (as shown in Figure 5.1). The region comprises three administrative zones (Anyuak, Nuer and Majang) and 13 districts, one special district and one city administration. The region is endowed with highly diversified natural resources, in particular the large expanse of arable land and suitable cropland (Zabel, Putzenlechner et al. 2014), sufficient rainfall and ground water resources, which render it the region best suited for cropland expansion and agricultural development/investments (Tadesse 2007, Cascão 2013). Since mid-2000, the Ethiopian government has been more actively encouraging large-scale land investments and improving various aspects of the technical management of land issued, and has also leased out huge areas of Gambella region to foreign investors (Baumgartner 2017). For instance, an estimated 1.4 million hectares of land in Ethiopia was transferred to foreign and domestic investors between 2006–2011 (Baumgartner 2017), most of which is located in eight districts of the Gambella region. Anyuak Zone has the largest number of investors, followed by Nuer Zone and then Majang Zone (Gebresenbet 2016).

Large-scale commercial agriculture is perceived by the Ethiopian government to have a number of clear benefits, including promoting food security, creating jobs and transferring technology (Keeley, Seide et al. 2014). However, these rushes to land, water and other essential natural resources by foreign companies have had negative effects for the food production of indigenous and local people, have caused environmental degradation, and have been identified as the main contributing factor for LULCC in the region (Rahmato 2011, Awoke, Teferi et al. 2018, Brhane Meles Gebre & Zemenu Awoke Andualem 2018, Degife, Zabel et al. 2018).While large-scale agricultural investment production is designed solely for foreign markets without considering the food security requirements of a country, local people, incongruously, largely depend on international food aid (Admassie and Abebaw 2014, Bezu and Holden 2014, Baye 2017).

Smallholder farmers, on the other hand, account for 96% of the total area cultivated and generate the key share of total production for the main crops in Ethiopia (Taffesse, Dorosh et al. 2012). However, decades of neglect have resulted in the small-scale agricultural sector neither fulfilling its major functions of providing adequate food to both rural and urban populations, nor providing sufficient resources required for an industrialization process (Moreda 2018). Small-scale farmers are still deeply marked by a strong vulnerability to food shortage and large yield gaps (Cascão 2013). Land fragmentation, farmers' traditions and beliefs, pests, post-harvest management and losses, institutional practices/norms and policy, farmers' resistance to new technology, weak linkages among public, private and non-governmental extension staff, lack of crop management with respect to planting time and weed control, and low usage of organic or mineral fertilizers are the main causes of low productivity and high yield gaps in Ethiopia and in Gambella region (Schneider and Anderson 2010, Gálvez-Nogales and Fonseca 2014, Hillocks 2014, Sewnet, Elemo et al. 2016, Admassie, Assefa et al. 2017, Alemu, Berhanie Ayele et al. 2017).

Generally, in the last few decades, Ethiopia has been struggling to feed its growing population. However, achieving food security has been a major challenge (Endalew, Muche et al. 2015) and agriculture still remains underdeveloped in Ethiopia (Admassie and Abebaw 2014, Bezu and Holden 2014, Baye 2017). According to Stellmacher and Kelboro (2019), more than 50% of Ethiopian family farmers are food deficient and, at present, climate change is expected to worsen food insecurity in the country (FAO 2008). Gambella is one of the less developed regions of Ethiopia and where people are most severely affected by food shortage (Braun and Gatzweiler 2014, Endalew, Muche et al. 2015).

5.1.1 Study area

Gambella Regional State covers a total land area of 25,521 km^2. It shares a long border with South Sudan and two other Ethiopian regions: Oromia to the north and east and the Southern Nations, Nationalities and Peoples' Regional State (SNNPRS) to the south. The topography divides the Gambella region into two broad sub-regions, which are between 900 and 2,200 m a.s.l. (meters above sea level) and the flood plains below 500 m a.s.l. The Gambella region lies within the hot to warm humid lowland agro-ecological zone. Its climate is classified as tropical savannah (Aw) by Koppen and Geiger (Kottek, Grieser et al. 2006) with an average temperature of 27.6°C and in the lower altitudes the annual rainfall varies from 900–1,500mm while at higher altitudes it ranges from 1,900–2,100mm (Dika 2018). The rainy season starts at the end of April and lasts until October, with the maximum rainfall in July (Alemayehu, Gebrekidan et al. 2014). The major rivers in the region are the Baro, Akobo, Alwero and Gillo (Degife and Mauser 2017). Maize and sorghum are important cereal crops, widely farmed by the local people (Degife, Zabel et al. 2019), and these two crops supply over 70% of average daily caloric intake in the region (Dorosh and Rashid 2013). According to the 2017 Ethiopian population projection, the total population of the region is approximately 436,000 (CSA 2018). According to a CSA (2018) report, based on a Household Income, Consumption and

Expenditure (HICE) Survey, around 23% of the total population of Gambella region were below the poverty line in 2015/16.

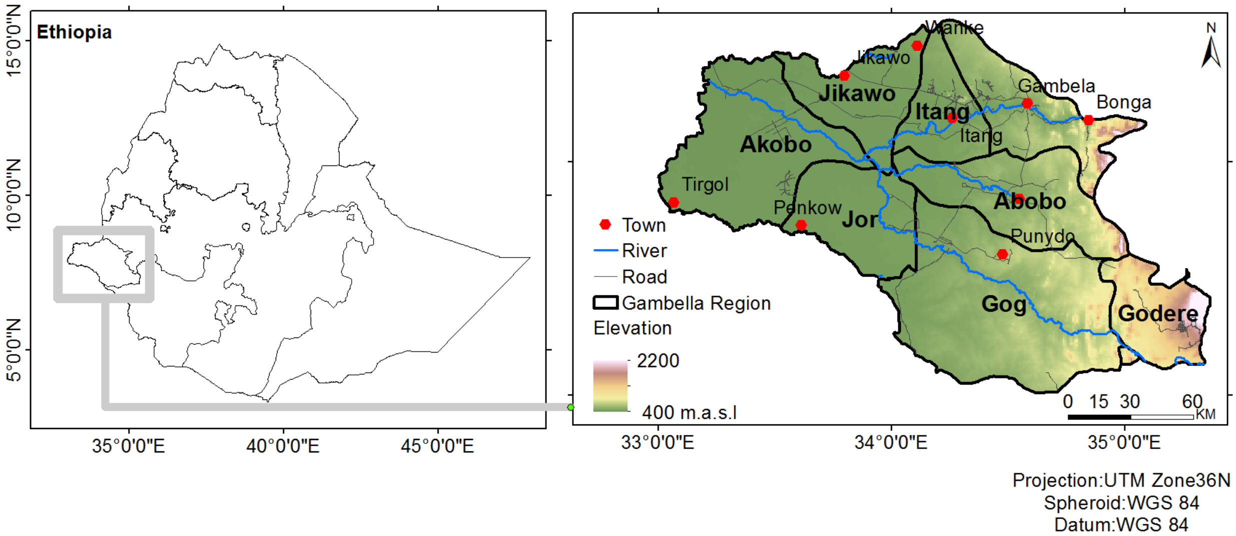

Figure 5.1: Gambella Locational Map: Federal Democratic Republic of Ethiopia (left) and Gambella Regional State (right).

5.2 The intricacies between land use change, food production and climate change in Gambella region, Ethiopia

Land-use change and degradation is one of the driving forces for climate change and it is one of the major environmental problems in Ethiopia (Gebreselassie, Kirui et al. 2016). According to the Intergovernmental Panel on Climate Change (IPCC), there is 90% scientific certainty that human activities are responsible for changes in land use (IPCC 2014). In Ethiopia, land-use change and degradation has been going on for decades (Gebreselassie, Kirui et al. 2016) and contributes to high environmental costs such as loss of biodiversity and fresh-water depletion (Henry, Engström et al. 2018). According to Gashaw, Bantider et al. (2014), various studies conducted in different parts of the country reported a significant decrease of vegetation cover to make room for agricultural expansion, to meet food requirements for a growing population (DeFries and Rosenzweig 2010, Gibbs, Ruesch et al. 2010, Temesgen, Amare et al. 2014). At present, about 70% of the Ethiopian land area is being used in agricultural production (Se, Dorosh et al. 2012), and more than 95% of crop production that is rainfall dependent has been produced by smallholders and subsistence farmers who have less capacity to adapt to climate change (Bewket 2009, Kelbore 2012, Alemu and Desta 2017)

The review of the impact of climate change on crop production and implication for food security has shown that climate change will have a significant impact on both future food production and agricultural land use in Ethiopia (Figure 5.2) (Hamza and Iyela 2012, Seo and Rodriguez 2012). Over the past four decades, the country has experienced changes both in dry and wet periods, affecting the agro-ecological conditions of the country (Parry, Rosenzweig et al. 2004, Wubie 2015, Gezie 2019). According to Aragie (2013), the average annual temperature in Ethiopia has been increasing by 0.37ºC every ten years. Future temperature projections of the IPCC mid-range scenario show that the mean annual temperature will increase in the range of 0.9 to 1.1ºC by 2030, in the range of 1.7 to 2.1ºC by 2050, and in the range of 2.7 to 3.4ºC by 2080 in Ethiopia compared to the 1961–1990 norm (Aragie 2013). Between the mid-1970s and late 2000s, the rainfall season, based on quality-controlled station observations, decreased by 15–20% across parts of southern, south-western, and south-eastern Ethiopia (Brown, Funk et al. 2017). Decrease in precipitation has multiple effects on agricultural production and water availability for irrigation and other farming uses (Aragie 2013). Climate change exacerbates the problem of rainfall variability. Droughts (famine) and floods are very common phenomena in Ethiopia, with significant events occurring every three to five years (Bewket, Radeny et al. 2015, Suryabhagavan 2017). For instance, in El Niño years, summer rainfall is lower over parts of the country and these years are often associated with food shortage (Lewis 2017).

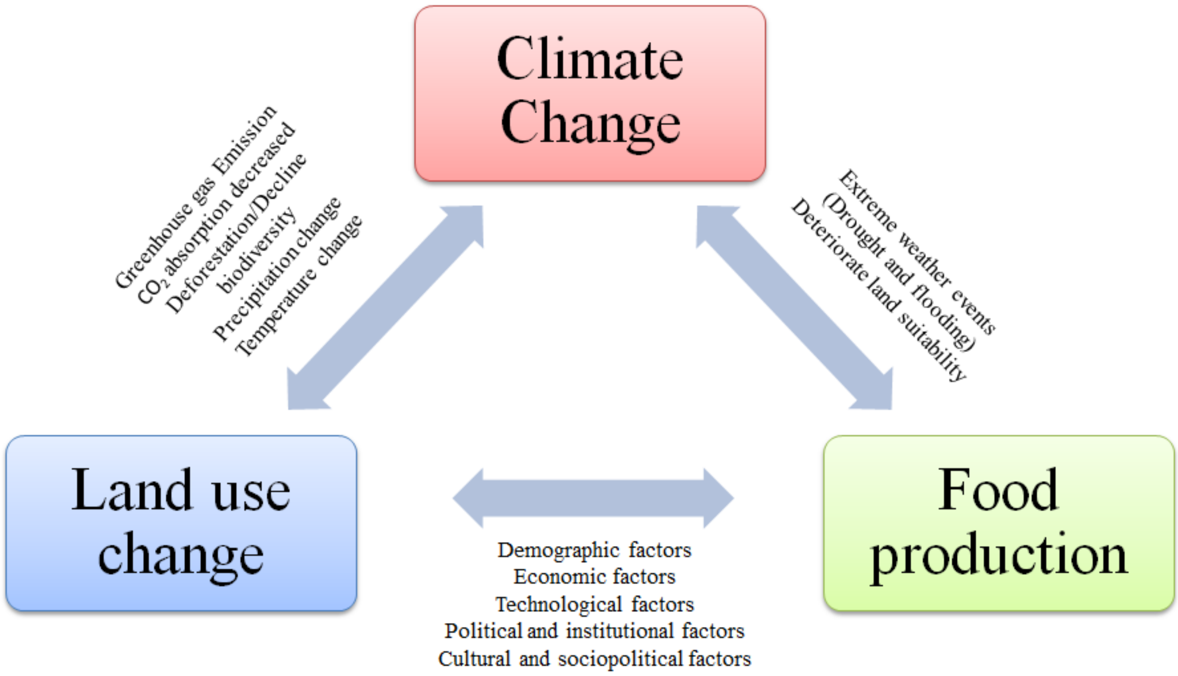

Figure 5.2: The intricacies between land-use change, food production and climate change, modified from Seo and Rodriguez (2012).

Currently, climate change makes it harder to achieve the Sustainable Development Goals and ensure a sustainable future and it will affect all four dimensions of food security (food availability, food accessibility, food utilization and food systems stability) (FAO 2008, Abbade 2017, Gil, Reidsma et al. 2019). For instance, the second sustainable development goal (SDG-2) mainly focused on food security and agricultural sustainability and this is directly affected by climate change (Gil, Reidsma et al. 2019). Findings from the 4th and 5th assessment report of IPCC indicate that already towards 2050, with respect to food crops, yield losses between 20–30% can be expected as compared to current conditions in large parts of Africa, including Ethiopia (Kahiluoto and Rötter 2009, IPCC 2014). The overall effect of climate change on yields of major cereal crops in the Ethiopia region is very likely to be negative, with strong regional variation (Kelbore 2012, Abera, Crespo et al. 2018, Alemu and Mengistu 2019, FDRE 2019). For instance, in Gambella region, precipitation (rainfall) decreasing and temperature increasing (Dika 2018) results in a shortening of the maturity period, crop failure and expanding crop diseases. Although climate change is a long-term phenomenon (Kahiluoto and Rötter 2009), the mitigation and adaption measures taken over the next ten to 20 years will be critical for the Gambella region.

5.3 Research objectives

In this thesis, three main objectives are addressed with the published or submitted papers. These are:

A) To examine the rate, extent and distribution of various LULCC coverages in Gambella Regional State and to understand the cause and consequences of LULCC in the region;
B) To estimate the magnitude and extent of the intensification potential of the key Gambella cereal crops (maize and sorghum) and to identify potential cropland expansion areas in the region.
C) To investigate impacts of future climate change on potential crop yields, with maize as an exemplar, under climate change scenarios in Gambella, Ethiopia.

6. Publications

6.1 Framework of the thesis

This cumulative thesis comprises three publications. Each publication directly answers the research objectives. Figure 6.1 shows the framework of publications and their relationship to each other.

The first publication focuses on the LULCC of the region, giving a complete picture of LULCC in the entire Gambella region from the mid-1980s to 2017. This paper also documents LU intensity changes in the region by identifying and analyzing the rate of small-scale and commercial agricultural land expansions and their overall extent. The LULC classification is used as a basis to identify where cropland expansions areas are potentially possible, and that is further described in publication II.

The second publication deals with the magnitude and extent of the intensification potentials of the key Gambella cereal crops (maize and sorghum) and identifies potential cropland expansion areas in the region. Crop yield gaps and potential production in the region is identified by comparing simulations of potential crop yields and the average reference data that is obtained from statistical crop yields from 1997–2017. The potential calorie intake and calorie crop production of the region is also covered within this publication. The potential food production of a country or region in the future is directly influenced by future climate conditions (temperature, precipitation, CO_2 concentration, etc.). How future climate change impacts on projections of potential yields is further investigated by publication three.

The third publication deals with climate change impacts on both rainfed and irrigated potential maize yields from 2020–2099 under future climate change scenarios in the Gambella region. The publication identifies the contributions of temperature, water stress and CO_2 on maize yield changes for RCP 2.6, 4.5 and 8.5. In this publication, we slice the time frame into 30 climate 'normals' (2010–2039, 2040–2069 and 2070–2099) and compare each climate normal with the reference period (1975–2004) to understand the impact of climate change on the future maize yield potential. The correlation of increased temperature and decreasing growing days is also discussed in detail in this paper.

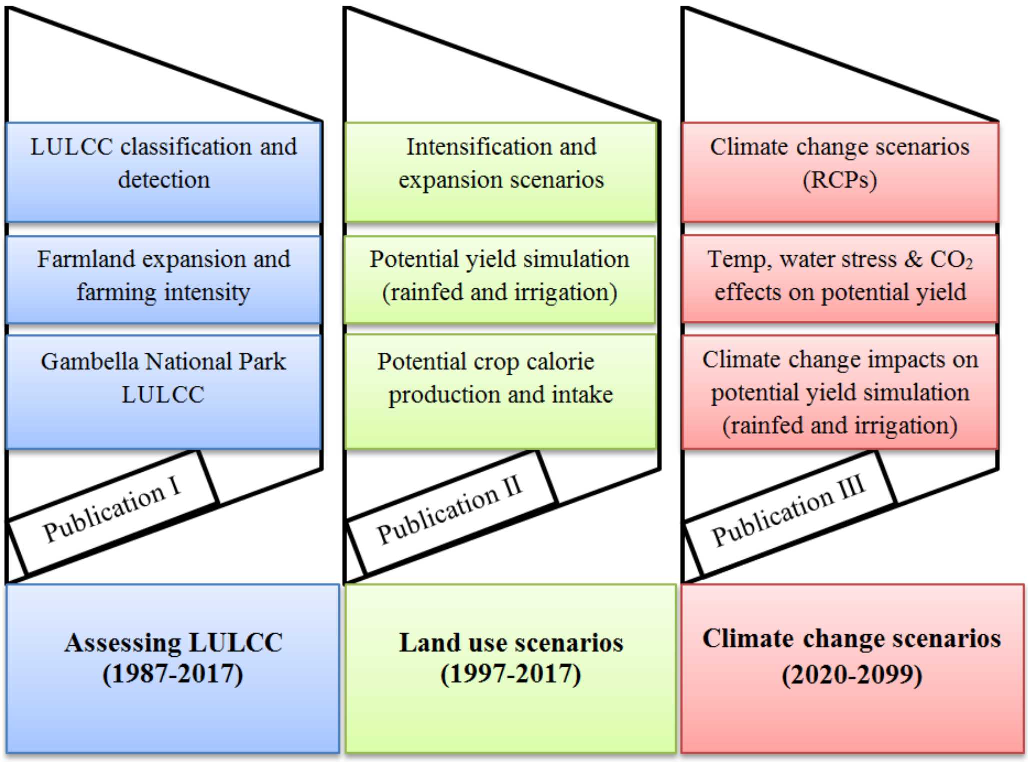

Figure 6.1: Framework of the thesis.

6.2 Overview of the publication

The thesis includes the following three main publications:

Publication I

Degife, A. W., F. Zabel and W. Mauser (2018). "Assessing land use and land cover changes and agricultural farmland expansions in Gambella Region, Ethiopia, using Landsat 5 and Sentinel 2a multispectral data." Heliyon 4(11): e00919.

Assessing land use .pdf

Publication II

Degife, A. W., F. Zabel and W. Mauser (2019). "Land Use Scenarios and Their Effect on Potential Crop Production: The Case of Gambella Region, Ethiopia." Agriculture 9(5): 105.

Land Use Scenarios
and Their Effect.pdf

Publication III

Degife, A. W., F. Zabel and W. Mauser (2019). "Climate change impacts on potential maize yields in Gambella Region, Ethiopia." Regional Environmental Change REEC-D-19-00600. **Under review**

Climate change
impacts.pdf

Publication I

Degife, A. W., F. Zabel and W. Mauser (2018). "Assessing land use and land cover changes and agricultural farmland expansions in Gambella Region, Ethiopia, using Landsat 5 and Sentinel 2a multispectral data." Heliyon 4(11): e00919

Assessing land use
.pdf

.

Heliyon

Received:
13 August 2018
Revised:
12 October 2018
Accepted:
2 November 2018

Cite as: Azeb W. Degife, Florian Zabel, Wolfram Mauser. Assessing land use and land cover changes and agricultural farmland expansions in Gambella Region, Ethiopia, using Landsat 5 and Sentinel 2a multispectral data. Heliyon 4 (2018) e00919.
doi: 10.1016/j.heliyon.2018.e00919

Assessing land use and land cover changes and agricultural farmland expansions in Gambella Region, Ethiopia, using Landsat 5 and Sentinel 2a multispectral data

Azeb W. Degife*, Florian Zabel, Wolfram Mauser

Department of Geography, Ludwig-Maximilians-University, Luisenstr. 37, 80333 Munich, Germany

* Corresponding author.

E-mail address: a.degife@iggf.geo.uni-muenchen.de (A.W. Degife).

Abstract

The pace of change in land use and cover in Ethiopia depends on three main factors that cause pressure on agriculture land: resettlement programmes, population growth and increasing agricultural investments. Gambella is one of the regions of Ethiopia that attracts large-scale agricultural investments that extensively drive land use and cover changes in the region. The aim of this study is to examine the rate, extent and distribution of various land use and cover changes in Gambella Regional State, Ethiopia, from 1987 to 2017. The analysis is mainly based on Landsat 5 and Sentinel 2A satellite images and fieldwork. Two Landsat Thematic Mapper and a Sentinel 2A image were used for determining the maximum likelihood of land use/cover classification. The results show that farmland decreased by 26 km^2 from 1987 to 2000; however, during the last two decades, agricultural land area increased by 599 km^2, mainly at the cost of tropical grasslands and forests. We found that areas cultivated by smallholder farmers increased by 9.17% from 1987 to 2000. However, small-scale farm activities decreased by 7% from 2000 to 2017. Areas cultivated by large-scale state farms totalled 202 km^2 in 1987; but by 2000, this large-scale state farming had been completely abandoned by the state, and as a result, its land use has decreased to zero. Despite this, in 2017 large-scale farming increased to 746 km^2. In addition, Gambella National Park, which is the nation's largest national park and ecosystem, was also largely affected by Land Use and Land Cover changes. The conversion of savannah/tropical grasslands to agricultural farmland has caused varied and extensive environmental degradation to the park. The Land Use and Land Cover changes in the Gambella region are discussed on the basis of underlying socioeconomic factors.

Keywords: Environmental science, Earth sciences, Geography

1. Introduction

Land Use and Land Cover changes (LULCC) involves either a shifting to a different land use or an intensification of existing land [1]. Currently, across the world, an increasing demand for space for settlement, agricultural investment and industrial activities is being observed [2, 3]. This leads to unprecedented LULCC, and these have caused both socioeconomic and environmental problems [4]. Human use of land has had a profound effect upon the natural environment resulting in an observable pattern in Land Use and Land Cover (LU/LC) over time [5, 6]. The aim of this paper is to explore the dynamics and mechanisms of LULCC during the last 30 years in the Gambella region in the southwest of Ethiopia, where the LU/LC dynamics are the largest in the country [7, 8].

In Ethiopia and especially in the Gambella region, the pace of change in LU/LC depends on three main factors: resettlement, population growth and increasing agricultural land pressure [8, 9, 10]. All three factors have own contribution for the LULCC. Between 1983 and 1985, the worst famine in the country's history led to the deaths of more than 400,000 people. After this drought, the Ethiopian government, Derg (the Coordinating Committee of the Armed Forces, Police and Territorial Army that ruled Ethiopia from 1974 to 1991), made and carried out resettlement plans to relocate the rural population with the principal strategy of ensuring food security [11]. In the mid-1980s, nearly 800,000 people were relocated, mostly from the northern highlands to distant areas in the southwest, including the Gambella region [12]. As a result, LULCC have heavily modified the natural landscape of the Gambella region, and large areas across the region have been deforested and/or drained [13]. Similarly, in the 2000s the Federal Democratic Republic of Ethiopia (FDRE) took the voluntary villagization scheme (VVS) as a strategy to transform the livelihood of settlers and ensure food security by providing socioeconomic and infrastructural delivery, and solving the problems created by the Derg on a voluntarily basis through an intra-regional approach. This resettlement programme, that has been

 https://doi.org/10.1016/j.heliyon.2018.e00919

ongoing since the 1980s, has caused a large shift in population into the Gambella region. According to the Ethiopian Central Statistical Agency (2015), the total population of the Gambella region rose from 182,000 in 1994, to 307,000 in 2007, and to 409,000 in 2015. This rising population over the years has created considerable pressure on the land and its natural resources, including its forests and water [14].

The Gambella region has both a unique ecology and an extraordinarily rich biodiversity. At the same time, the level of resource use in the Gambella region is still comparatively low. This explains why the main mechanism of LULCC in the Gambella region is agricultural land expansion [8]. Besides the spread of small-scale farming as a result of the population increase, one of the main agricultural development policies is large-scale farming investment. It is promoted by the Ethiopian government as part of an infrastructure expansion and economic stabilisation programme. Since 2005, the country, as well as the Gambella region, saw a surge of domestic and foreign investment into commercial farming. From the late 1990s to the end of 2008, almost 3.5 million hectares of land were transferred to both domestic and foreign investors, mainly in the southwestern part of Ethiopia [8]. Because of its favourable environmental conditions, the Gambella region has attracted large-scale agricultural investment. During the same period, both the federal and regional government have awarded 1.1 million hectares of suitable farmland in the Gambella region to foreign and local companies/investors. Since 2008, Gambella has become the major target point for foreign investors.

These developments, which began in the 1980s and are still ongoing, have a major impact on the magnitude and nature of LULCC in the Gambella region and throughout the whole of Ethiopia. It is therefore highly relevant to assess and understand LULCC in this region. Existing studies so far have mainly focused on either deforestation or LULCC in specific districts of the Gambella region [13].

A complete picture of LULCC in the entire Gambella region, from the mid-1980s to the present day, does not exist to the best of the authors' knowledge. Therefore, the overall objective of this paper is to examine the rate, extent and distribution of various LULCC coverages in Gambella Regional State. This also includes a contribution, as a first step, to documenting LU intensity changes in the region by identifying and analysing the rate of small-scale and commercial agricultural land expansions and their overall extent.

2. Materials and methods

2.1. Study area

Gambella region is one of nine administrative regions in the western part of Ethiopia (see Fig. 1). The region covers a total area of 25,521 km^2 [15]. It is located between

https://doi.org/10.1016/j.heliyon.2018.e00919

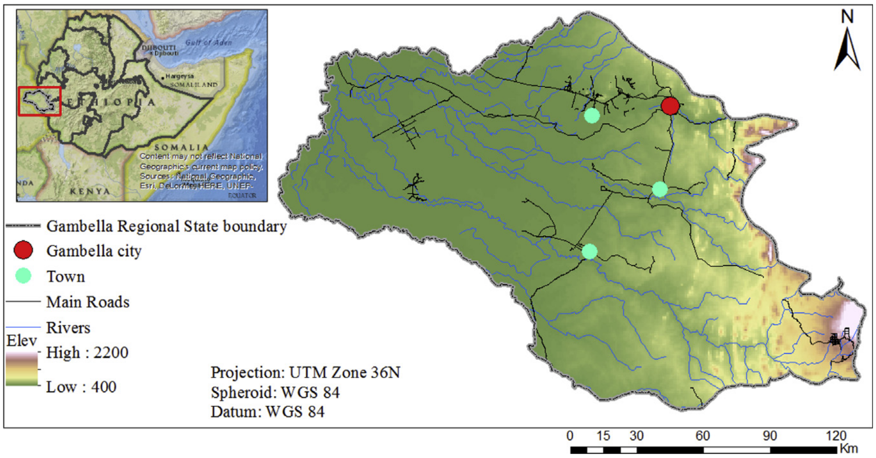

Fig. 1. Locational map: Federal Democratic Republic of Ethiopia and Regional States boundary (left) and Gambella Regional State (right).

6°28′38″ to 8°34′ North Latitude and 33° to 35°11′11″ East Longitude. As shown in Fig. 1, it borders two other Ethiopian regions – Oromia to the north and east and the Southern Nations, Nationalities and Peoples' Regional State (SNNPRS) to the south. To the west it shares a border with South Sudan. The region is comprised of three administrative zones (Anyuak, Nuer and Majang) and 13 districts (woredas), one special district and one city administration [16]. Gambella is one of the emerging regions in Ethiopia. Its economy is predominantly based on agriculture with mixed farming among the Anyuak and Majang people and agro-pastoral among the Nuer people [17]. The region lacks infrastructure with a poor transportation network among the districts (woredas).

The Gambella region lies within the hot to warm humid lowland agro-ecological zone. The topography divides the Gambella region into two broad sub-regions, which are between 900 to 2200 masl (metres above sea level) and the flood plains below 500 masl. Its climate is classified as tropical savannah (Aw) by Köppen and Geiger [18] with an average temperature of 27.6 °C and 1,197 mm of average annual precipitation [19]. The rainy season starts at the end of April and lasts until October with the maximum rainfall in July [20]. In addition, there are two main harvesting times known as Meher and Belg. In the Meher, crops are harvested from September to February and in the Belg, crops are harvested from March to August. Baro, Gilo, Akobo, and Alwero are the main rivers crossing the region [21]. The Gambella region, due to favourable soil, topography and climate conditions, is known to be one of the most fertile regions in Ethiopia and is suitable for growing various types of crops. The region has very high crop suitability compared to other parts of Ethiopia [22]. Crop suitability, abundant water resources, unused/underutilised land and Ethiopian government policy (Agriculture Development Led Industrialisation) are the main facilitating factors for the expansion of large-scale commercial farming in the region.

https://doi.org/10.1016/j.heliyon.2018.e00919

2.2. Remote sensing data processing and analysis

In order to analyse LULCC in the Gambella region, medium resolution satellite remote sensing data from the Landsat and SENTINEL-2 sensors were selected, covering the period from the mid-1980s to the present. Multi-temporal satellite imagery plays a vital role in quantifying spatial and temporal LULCC in the area [23]. LULCC maps were determined from the selected images through a number of consecutive digital processing steps ranging from image selection and download, pre-processing, classification using known training sites, validation using a separate set of known validation sites, classification post-processing and map as well as change map production. The spatial map resolution is 30 m in the case of Landsat TM and 10 m in the case of Sentinel-2 images [24] (https://earthexplorer.usgs.gov/). This medium resolution satellite imagery offers the potential for an accurate land cover classification and pattern analyses [25] for the detection and quantification of historical LULCC, especially in remote regions [26] such as the Gambella region where not many data on present LULCC are currently available. Multispectral satellite images of the region were selected for the three years of 1987, 2000 and 2017. Care was taken to select the images to match their phenological periods as closely as possible in order to note the changes in vegetation development. At the same time the images acquired were from the period immediately after the dry season in order to be able to observe the whole range of active vegetation and to avoid investigating dried up vegetation, which cannot be separated into LULCC categories. This being a vital prerequisite for detecting the full range of categories and later comparison of the spatial extent of the classified LULCC categories, it nevertheless limits the number of available images. Based on these considerations Landsat and Sentinel 2a images from January and February 1987, 2000 and 2017 respectively were selected and downloaded (as illustrated in Table 1, all the listed images from each year were mosaicked and then clipped based on the Gambella feature, before being processed and classified).

The second step of digital image processing consisted, after radiometric image enhancement techniques of the Landsat TM data [27], of a two-stage image classification procedure that included unsupervised Iterative Self Organising Data Analysis (ISODATA) and supervised (Maximum Likelihood) classification [28]. Unsupervised (ISODATA) clustering algorithms determined the characteristics of the natural groupings of cells in multidimensional attribute space [29]. The unsupervised ISODATA algorithm created 25 clusters of pixels using ten different iterations and a convergence threshold of 0.99. From the 25 clusters, seven separate LU/LC classes were merged for the years 1987, 2000 and 2017 based on their extracted spectral signatures. The delineated LU/LC classes were: water bodies, man-made structures, farmland, forest land, tropical grasslands, wetland vegetated area and barren or sparsely vegetated land. These classes are described in Table 2 based on

https://doi.org/10.1016/j.heliyon.2018.e00919

Table 1. Dates and scene ID number of Landsat 5 and Sentinel 2a images used.

Year	Day and month	Scene/tile	Entity ID
1987	13/Jan	171/054	LT05_L1TP_171054_19870113_20170215
	13/Jan	171/055	LT05_L1TP_171055_19870113_20170215
	20/Jan	172/054	LT05_L1TP_172054_19870120_20170215
	20/Jan	172/055	LT05_L1TP_172055_19870120_20170215
	22/Jan	170/055	LT05_L1TP_170055_19870122_20170215
2000	01/Jan	171/054	LT05_L1TP_171054_20000101_20170908
	01/Jan	171/055	LT05_L1TP_171055_20000101_20170908
	24/Jan	172/054	LT05_L1TP_172054_20000124_20171214
	24/Jan	172/055	LT05_L1TP_172055_20000124_20171214
	27/Feb	170/055	LT05_L1GS_170055_20000227_20171214
2017	05/Jan	T36NWP	S2A_MSIL1C_20170105T080312_ N0204_R035_T36NWP_20170105T081256.SAFE
	05/Jan	T36NYP	S2A_MSIL1C_20170105T080312_N0204_ R035_T36NYP_20170105T081256.SAFE
	05/Jan	T36PWQ	S2A_MSIL1C_20170105T080312_N0204_R035_ T36PWQ_20170105T081256.SAFE
	15/Jan	T36NXN	S2A_MSIL1C_20170115T080251_N0204_ R035_T36NXN_20170115T081421.SAFE
	15/Jan	T36NXP	S2A_MSIL1C_20170115T080251_N0204_ R035_T36NXP_20170115T081421.SAFE
	15/Jan	T36NYN	S2A_MSIL1C_20170115T080251_N0204_ R035_T36NYN_20170115T081421.SAFE
	15/Jan	T36PXQ	S2A_MSIL1C_20170115T080251_N0204_ R035_T36PXQ_20170115T081421.SAFE
	15/Jan	T36PYQ	S2A_MSIL1C_20170115T080251_ N0204_R035_T36PYQ_20170115T081421.SAFE

Table 2. Description of the LU/LC classes.

	Land cover	Description
1	Water bodies	This class of land cover describes areas covered with water including rivers and lakes
2	Artificial areas	This class describes the land covered with buildings in the study area. It includes commercial, residential, industrial and transportation infrastructure.
3	Farmland	This class describes land which is mainly used for growing crops. Crops in this land are either grown by irrigation (commercial farmland) or are rain-fed (small-scale farmland).
4	Forest land	This class describes the areas with evergreen trees, mainly growing naturally.
5	Tropical grasslands	This class of land cover defines grassland or tropical savannah as the main vegetation cover.
6	Wetlands	This class describes areas with swampy or marshland vegetation.
7	Barren or sparsely vegetated land	This describes the land left without vegetation cover. This can result from abandoned cropland and eroded land due to degradation, exposed soil, sand or rocks,

https://doi.org/10.1016/j.heliyon.2018.e00919

Corine LU/LC classes. This unsupervised classification of LU/LC classes was then used as a basis for the following supervised classification.

Supervised classification is based on training sites where land use is known and where signatures can be used to train the algorithm. For the years 1987 and 2000, no supervised classification training sites with known LU/LC were available. The training sites were therefore selected based on the spectral signature of the classes and, in the case of known stable land uses, through comparison with the known land uses in 2017. For each of the predetermined LU/LC types from the unsupervised approach, training sites were selected and spectral signatures derived. In general, a satisfactory spectral signature is one ensuring that there is 'minimal confusion' among the LU/LC classes to be mapped [30] and at the same time covering the spectral variability of the class.

In 2017, through simple random sampling the ground truth data was collected for the supervised classification. This randomness of ground truth data ensures that all parts of the study area have an equal chance of being sampled. Therefore, training sites were identified based on field-collected data using Global Positioning System (GPS), on-field checks of the high-resolution January 2017 Sentinel 2a images, and familiarity with the area. The spectral signatures of the selected LU/LC classes represented by their training areas were then used to produce a Maximum Likelihood Classification of the satellite images. The number of training sites varied from one LU/LC class to another, depending on ease of identification and the level of variability of pixel values within the site. For instance, due to spectrally similarities in water and forest areas, the training sites were set to 60 per class. Whereas, both in farmlands and tropical grasslands, the spectral variability were higher, as result the training site per class were set to 120 and 100 respectively. For more accurate results several training sites for each class located in different parts of the image. The Maximum Likelihood Classification is the most widely used per-pixel method. In addition to the reflectance values, it also takes into account the covariance of the information contained in the sensors' spectral bands of LU/LC classes [31].

2.3. Post classification and accuracy assessment

Post-classification refinement was conducted in order to improve classification accuracy and to reduce the number of erratic misclassifications. After classification, ground verification was done in order to check the accuracy of the classified LU/LC map [32]. Based on the ground verification, necessary corrections and adjustments were made. To determine the accuracy of the 1987 and 2000 classifications, a total of 760 stratified randomly generated points (locations) were selected in the classified image of the study area (as shown in Tables 3 and 4). Google Earth Time Lapse was used as the main reference source to identify these selected points. Accuracy assessment of the 2017 classification of the Sentinel 2a satellite images

https://doi.org/10.1016/j.heliyon.2018.e00919

Table 3. Error matrix accuracy totals for the classified image (1987).

Class types determined from reference source

Year: 1987		**Water bodies**	**Artificial areas**	**Farmland**	**Forest land**	**Tropical grasslands**	**Wetland vegetated area**	**Barren or sparsely vegetated area**	**Classification overall**	**Producer accuracy % (Precision)**
Class types determined from classified map	Water bodies	73	0	0	0	23	0	0	96	73
	Artificial areas	0	27	26	0	2	0	0	55	50
	Farmland	0	2	88	0	19	1	0	110	80
	Forest land	0	0	0	74	0	0	0	74	100
	Tropical grasslands	0	2	37	0	264	0	1	304	87
	Wetland vegetated area	0	0	0	0	1	53	0	54	98
	Barren or sparsely vegetated area	0	0	9	0	1	5	52	67	78
	Truth overall	73	31	160	74	310	59	53	760	
	User accuracy % (Recall)	100	87	55	100	85	85	98		

Overall accuracy = 82.79%

Kappa = 0.776

8 https://doi.org/10.1016/j.heliyon.2018.e00919

Table 4. Error matrix accuracy totals for the classified image (2000).

Class types determined from reference source										
Year: 2000		**Water bodies**	**Artificial areas**	**Farmland**	**Forest land**	**Tropical grasslands**	**Wetland vegetated area**	**Barren or sparsely vegetated area**	**Classification overall**	**Producer accuracy % (Precision)**
Class types determined from classified map	Water bodies	108	0	0	0	0	0	0	108	100
	Artificial areas	0	104	0	0	7	0	4	115	90
	Farmland	0	0	108	0	4	0	0	112	96
	Forest land	0	0	0	108	4	11	0	123	88
	Tropical grasslands	0	0	4	0	93	25	25	147	63
	Wetland vegetated area	0	0	0	0	0	72	0	72	100
	Barren or sparsely vegetated area	0	4	9	0	0	0	79	83	95
	Truth overall	108	108	112	108	108	108	108	760	
	User accuracy % (Recall)	100	87	55	100	85	85	98		

Overall accuracy = 88.4%

Kappa = 0.865

https://doi.org/10.1016/j.heliyon.2018.e00919

was based on ground truth data collected during the 2017 fieldtrip to the Gambella region. In addition, a total of 560 points (locations) were identified in the classified images of the study area (Table 5). Google Earth was used as a reference source to assess these selected points. The overall accuracy was calculated by dividing the sum of the correctly classified sample points by the total number of sample points.

2.4. LULCC detection

LULCC in the region was detected and assessed, and the size and distribution of the altered areas were quantified. The map from the validated classification in 1987 and 2000 using Landsat TM data was compared with the map produced for 2017 using Sentinel 2a, and then a complete matrix of categorical change was obtained. The Sentinel 2 classification result was re-projected and resampled from 10 m to the same 30 m resolution than the classification obtained by Landsat using a majority filter. This allows for comparison of Sentinel and Landsat images at the costs of spatial information of the Sentinel image. Finally, the 1987, 2000 and 2017 supervised classification results were compared using cross-tabulation to quantitatively determine the LU/LC dynamics. A pixel-based comparison was also used to produce quantitative change information.

2.5. Methods to classify large-scale commercial and small-scale farmland

The classification results say nothing about farming intensity. Therefore we chose a different approach for the distinction of farming intensity. It is based on the assumption that both the crop type selection and the level of farming intensity in terms of seed selection, use of machinery and fertiliser, as well as pesticide application, is related to field size. Mechanised agriculture allows and demands large field sizes to produce commodities at competitive prices. On the other hand, smallholders without market access and mechanisation cannot manage to work large fields. We masked farmland class from selected satellite imagery from each year and then separated large-scale farmland from small-scale farmland based on land holding size. In addition, high-resolution satellite images (Sentinel 2a) and Google Earth were used as a reference to distinguish small-scale and large-scale commercial farmlands. Finally, depending on a manual digitisation approach on the selected satellite imagery, we extracted large- and small-scale agricultural fields for the years 1987, 2000 and 2017. In Ethiopia, the Ministry of Agriculture and Rural Development (MOARD) is responsible for large-scale land deals with foreign and local investors [8]. Since 2008, MOARD has been transferring investment lands ranging from 500 hectares (ha) to a maximum of 5000 ha [33] which is far larger than small-scale farm land size, which is less than 2 ha [34]. Gambella agricultural office documents and LU/LC maps of the study area were used also to differentiate large-scale commercial

https://doi.org/10.1016/j.heliyon.2018.e00919

Article No~e00919

Table 5. Error matrix accuracy totals for the classified image (2017).

Class types determined from reference source

Year: 2017		**Water bodies**	**Artificial areas**	**Farmland**	**Forest land**	**Tropical grasslands**	**Wetland vegetated area**	**Barren or sparsely vegetated area**	**Classification overall**	**Producer accuracy % (Precision)**
Class types determined from classified map	Water bodies	76	2	1	1	0	0	0	80	95
	Artificial areas	0	78	1	0	0	0	1	80	97
	Farmland	0	0	62	1	0	2	15	80	78
	Forest land	0	0	0	80	0	0	0	80	100
	Tropical grasslands	0	0	1	0	78	0	1	80	98
	Wetland vegetated area	0	0	0	0	0	80	0	80	100
	Barren or sparsely vegetated area	0	4	2	0	4	1	73	80	91
	Truth overall	76	80	67	82	82	83	90	560	
	User accuracy % (Recall)	100	97	92	98	95	96	81		

Overall accuracy = 94.4%

Kappa = 0.931

https://doi.org/10.1016/j.heliyon.2018.e00919

farmland from small-scale farmland. In addition to this, in 2017, types of crop-growing by large-scale farmers were identified based on the fieldwork survey (in-situ data) and using the high-resolution (Sentinel 2a) satellite images.

3. Results

3.1. LULCC classification

As a first result, the accuracy assessment of the supervised LULCC classifications shows an overall accuracy of 82.7% for 1987, 88.4% for 2000 and 94.4% for 2017. The Kappa coefficients for 1987, 2000 and 2017 are 0.78, 0.86 and 0.93 respectively. The higher accuracy of Sentinel is related to the higher resolution of the images. These high values for the selected classes in Table 2 allow for a pixel-wise analysis of the changes in these LU/LC classes over time. These are listed in Table 6. During the last three decades (1987, 2000 and 2017), the gross changes in area coverage varied from one LU/LC class to another. Barren or sparsely vegetated land and farmland class experienced the biggest increase, and tropical grasslands underwent the largest decrease in area coverage, as shown in Table 6.

The total area percentage of each class in 1987, 2000 and 2017 shows that tropical grasslands had the largest share in 1987, representing 53.74% (13,716 km^2) of the total LU/LC categories assigned. This class underwent a major shift and was reduced to 41.94% (10,704 km^2) and 35.70% (9,112 km^2) in 2000 and 2017 respectively. The other class which faced a decline during the study period was forest land. The area of this class in 1987 was 16.41% (4,188 km^2) of the total area and in 2000 it showed a slight increase to 17.73% (4,524 km^2). However, by 2017 it had reduced to 15.50% (3,948 km^2). The major LULCC was also observed in the wetland vegetated area. Its share increased from 8.05% (2,056 km^2) in 1987 to 25.21% (6,435 km^2) in 2000,

Table 6. Total area coverage/net change and percentage change occurring between the years 1987, 2000 and 2017 for the classified LU/LC categories.

LU/LC class	**Area (1987)**		**Area (2000)**		**Area (2017)**		**1987−2000 Net area change (km^2)**	**2000−2017 Net area change (km^2)**
	km^2	**%**	**km^2**	**%**	**km^2**	**%**		
Water bodies	11	0.04	53	0.21	50	0.20	**+42**	**-3**
Artificial areas	33	0.12	431	1.69	218	0.85	**+398**	**-213**
Farmland	2,121	8.31	2,095	8.21	2,694	10.55	**-26**	**+599**
Forest land	4,188	16.41	4,524	17.73	3,948	15.50	**+336**	**-576**
Tropical grasslands	13,716	53.74	10,704	41.94	9,112	35.70	**-3,012**	**-1,592**
Wetland vegetated area	2,056	8.05	6,435	25.21	5,953	23.32	**+4,379**	**-482**
Barren or sparsely vegetated land	3,396	13.30	1,279	5.01	3,546	13.90	**-2,117**	**+2,267**
Total	**25,521**		**25,521**		**25,521**			

Bold fonts are used to emphasis the magnitude of net area changes between the years 1987−2000 and 2000−2017.

https://doi.org/10.1016/j.heliyon.2018.e00919

although it had decreased slightly to 23.32% (5,953 km^2) by 2017. The wetland area class expansion, which had been observed in the last 30 years, was not due to rainfall variation. In fact, according to World Meteorological Organisation (WMO) data, the average annual rainfall in the Gambella region during 1987 was higher than in 2000 and 2017 [35]. Therefore, wetland vegetated area cover in 1987 was lower compared to 2000 and 2017 due mainly to the construction of the Alwero Dam, which started in 1984 and led to the diversion of the Alwero river flow until 1992, reducing the water flow downstream [36]. On the other hand, agricultural area showed a slight decrease from 8.31% (2,121 km^2) in 1987 to 8.21% (2,095 km^2) in 2000, although by 2017, it had increased to 10.55% (2,694 km^2). The change in the water class was not very significant, although it did increase during the study period. The share of the total area was 0.04% (11 km^2) in 1987, 0.21% (53 km^2) in 2000 and 0.20% (50 km^2) in 2017. On the other hand, the share of barren or sparsely vegetated land cover shows significant changes, decreasing from 13.30% (3,396 km^2) in 1987 to 5% (1,279 km^2) in 2000. Despite this, barren or sparsely vegetated land had increased by 2017 and now covers 13.90% of the total area (3,546 km^2). The supervised classification results are illustrated below in Fig. 2.

3.1.1. LU/LC area percentage change (1987−2000) and (2000−2017)

The area percentage change shows the extent to which the different LU/LC class areas contribute to net gains (the amount of area that converts into a given class between two dates) and/or net losses (the amount of area that converts out of a given class between two dates) between 1987 and 2000. Artificial areas, wetland vegetated areas and forest land increased by 1206%, 213% and 8% respectively. Similarly, open water bodies increased by 382% in 2000. This increase in the share of the water class was mainly related to the Alwero Dam. The dam reservoir now stores 74,600 million cubic metres of water [37]. Originally, the dam was planned to irrigate a state cotton farm; however, that never materialised [36]. Lately, however, one of the largest farm companies (Saudi Star) constructed around 30 km of channels to transport the water from the dam to irrigate large rice fields. On the other hand, barren land, tropical grassland and farmland decreased by 62%, 22% and 2% respectively.

The area percentage change between 2000 and 2017 showed that most of LU/LC class area percentage changes had decreased. Artificial areas, tropical grasslands, forest land and wetland vegetated area decreased by 50%, 15%, 13% and 8% respectively. In contrast, barren land and farmland increased by 177% and 29% compared to 2000. The expansion of large-scale farming investment in the Gambella region is one of the key factors for the farmland area percentage change. In the past two decades, water cover remained constant and did not show any significant change.

https://doi.org/10.1016/j.heliyon.2018.e00919

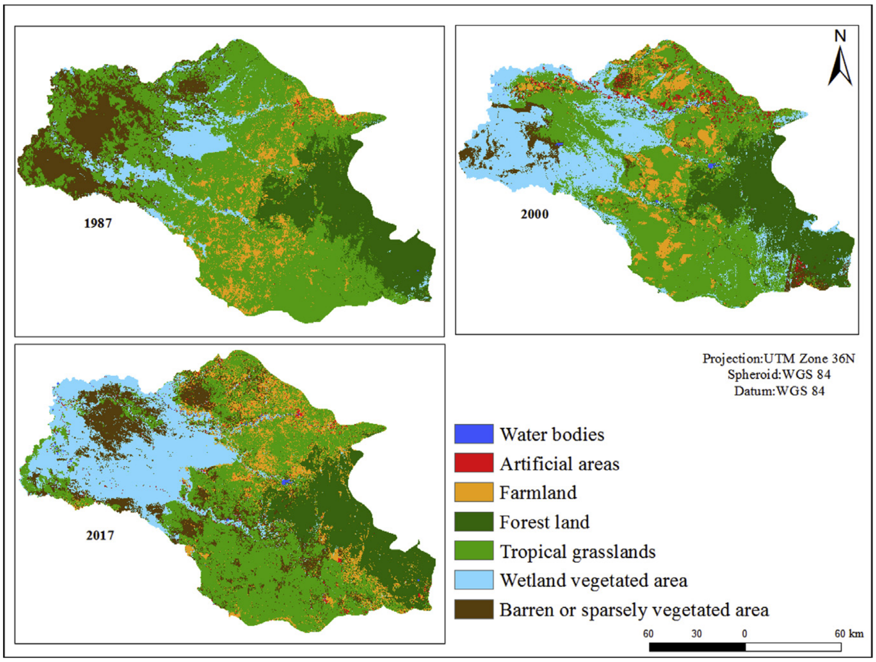

Fig. 2. Spatial distributional pattern of LULCC of the Gambella Region, Landsat 5 for 1987 (left), Landsat 5 for 2000 (right) and Sentinel 2A for 2017 (bottom left) supervised classification.

3.2. LULCC detection for the years 1987, 2000 and 2017

A post-classification comparison of the changes in the classified distribution of LU/LC categories was carried out in order to produce change maps with the purpose of gaining insight into the spatial patterns of change between the selected years. It also documents, spatially, the amount of conversion from a particular LU/LC to another LU/LC category [28]. The 'from-to' information of the Gambella region LU/LC maps is shown in Tables 7 and 8.

3.2.1. Change detection between 1987 and 2000

We found significant conversions from one land cover category to another. Tropical grasslands were mainly converted to wetlands (2,782 km^2) and farmland (1,617 km^2). There were also significant conversions of tropical grasslands to artificial areas (245 km^2). On the other hand, 830 km^2 of barren land was converted into tropical grasslands. About 183 km^2 and 44 km^2 of what was forest land in 1987 was converted to wetlands and barren lands respectively. Around 1,813 km^2 of barren land was also converted into wetland vegetation. Because of the largely unsuccessful resettlement programme during the 1990s, farmland that had been allocated by the Derg government in 1984−1985 was abandoned by farmers, who walked thousands of miles in order to return to their native regions [38]. As a consequence of the rebound of the resettlement programme and the following depopulation of large

https://doi.org/10.1016/j.heliyon.2018.e00919

Table 7. LULCC confusion matrix in km^2 of 1987 to 2000.

LU/LC type	Water bodies		Artificial areas		Farmland		Forest land		Tropical grasslands		Wetland vegetated area		Barren or sparsely vegetated area		Total 2000	Gain in 2000 (km^2)
	Area Km^2	%	Area Km^2	%	Area Km^2	%	Area Km^2	%	Area Km^2	%	Area Km^2	%	Area Km^2	%	Area Km^2	
Water bodies	7	64	0	0	2	0	1	0	27	0	7	0	10	0	53	46
Artificial areas	0	0	11	33	56	3	10	0	245	2	18	1	91	3	431	420
Farmland	0	0	2	6	342	16	2	0	1,617	12	18	1	114	3	2,095	1,753
Forest land	1	9	0	0	33	2	3,876	93	464	3	140	7	10	0	4,524	648
Tropical grasslands	0	0	17	52	1,567	74	72	2	7,963	58	256	12	830	24	10,704	2,741
Wetland vegetated area	3	27	3	9	98	5	183	4	2,782	20	1,553	76	1,813	53	6,435	4,882
Barren or sparsely vegetated area	0	0	0	0	23	1	44	1	618	5	64	3	528	16	1,279	751
Total 1987	11		33		2,121		4,188		13,716		2,056		3,396		25,521	
Loss in 1987 (km^2)	4		22		1,779		312		5,753		503		2,868			

https://doi.org/10.1016/j.heliyon.2018.e00919

Table 8. LULCC confusion matrix in km^2 of 2000 to 2017.

LU/LC Type	Water bodies		Artificial areas		Farmland		Forest land		Tropical grasslands		Wetland vegetated area		Barren or sparsely vegetated area		Total 2017	Gain in 2017 (km^2)
	Area Km^2	%	Area Km^2	%	Area Km^2	%	Area Km^2	%	Area Km^2	%	Area Km^2	%	Area Km^2	%	Area Km^2	
Water bodies	31	58	0	0	0	0	1	0	0	0	14	0	4	0	50	19
Artificial areas	2	4	25	6	7	0	22	0	67	1	78	1	17	1	218	193
Farmland	5	9	130	30	292	14	379	8	1,287	12	444	7	157	12	2,694	2,402
Forest land	2	4	7	2	0	0	3,691	82	37	0	174	3	37	3	3,948	257
Tropical grasslands	2	4	131	30	1,381	66	110	2	6,207	58	950	15	331	26	9,112	2,905
Wetland vegetated area	10	19	59	14	39	2	225	5	1,024	10	4,175	65	421	33	5,953	1,778
Barren or sparsely vegetated area	1	2	79	18	376	18	96	2	2,082	19	600	9	312	24	3,546	3,234
Total (2000)	53		431		2,095		4,524		10,704		6,435		1,279		25,521	
Loss in 2000 (km^2)	22		406		1,803		833		4,497		2,260		967			

https://doi.org/10.1016/j.heliyon.2018.e00919

areas, 1,567 km^2 of the newly established farmland became tropical grasslands, and 98 km^2 became wetland vegetated areas.

3.2.2. Change detection between 2000 and 2017

Change detection between 2000 and 2017 shows that the major observed change was from tropical grasslands to barren land (2,082 km^2) and wetland vegetated areas (1,024 km^2). Large areas of forests were converted to farmland, wetland vegetated areas, tropical grasslands and barren land (379 km^2, 225 km^2, 110 km^2 and 96 km^2 respectively). Despite the conversion of forests to other LU/LC classes, there was also the conversion of 174 km^2 of wetland vegetation, 37 km^2 of tropical grasslands and 37 km^2 of barren land to forests. In recent times, the Ethiopian government has allocated part of the wetland vegetated area to large-scale commercial investors with the clear intention of draining water from the wetlands for irrigation purposes. As a result, around 444 km^2 of wetland vegetated area was changed into farmland area. In addition, there was a significant conversion to farmland from tropical grasslands (1,287 km^2). Table 8 shows that what was barren land (157 km^2) and an artificial area (130 km^2) in 2000 has now been converted into farmland in 2017. In contrast, due to the VVS programme in the Gambella region in the 2000s, around 1,381 km^2 of farmland was abandoned and converted to tropical grasslands.

3.3. Farmland expansion and farming intensity

This chapter takes a closer look at the expansion of farmland and its related division into different farming intensities. It is aimed at quantifying the change in smallholder and large-scale commercial farms separately. Whereas area expansion can easily be quantified with the change analysis documented in Chapter 3.2, the classification results say nothing about farming intensity. Agricultural area increased by a total of 573 km^2, or 27% of the area change in the Gambella region between 1987 and 2017. In total about 202 km^2 of cultivated area was identified as large-scale commercial farmland in 1987 and these large-scale farm fields had been under the control of state farms, as shown in Fig. 3. However, by 2000, this large-scale state farming had been completely abandoned, and as a result, its land use had decreased to zero.

In 2017, based on the fieldwork survey (in-situ data) and using Sentinel 2a satellite images, a total area of 746 km^2 of large-scale farm fields were identified and then this large-scale farm fields were masked from Sentinel 2a satellite images and classified, of which 415 km^2 were rice, 35 km^2 were cotton, 88 km^2 sesame, and the remaining 208 km^2 were covered by various types of cash crops. In total, large-scale commercial farmland has increased by 269% in the last three decades in the study area.

On the other hand, in 1987, around 1,919 km^2 of farmland was cultivated by small-scale farmers. This area increased to about 2,095 km^2 by 2000. This shows that

https://doi.org/10.1016/j.heliyon.2018.e00919

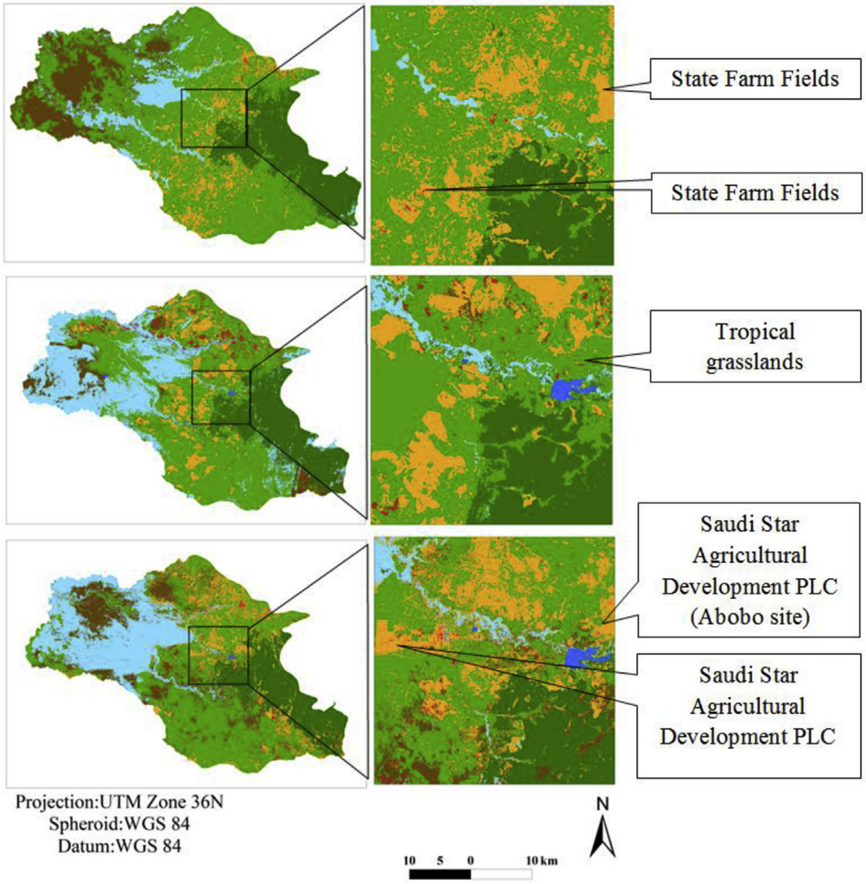

Fig. 3. Supervised image classification identified farmland expansion in the central part of Gambella region during 1987, 2000 and 2017. State-farm fields in Landsat 1987 (top), state-farm fields which are banded and turn into grasslands shown in Landsat 2000 (middle) and State-farm fields turned into large-scale farm fields from Sentinel 2a satellite image 2017 (bottom).

small-scale farmland in the region had increased between 1987 and 2000 by a total of 176 km^2 or 9.2%. In 2017, the total cover of small-scale farmland was 1948 km^2, which is a decrease of 147 km^2 or 7%. After 2011, the land which was aquired by smallholders had been given over to large-scale farm land or investors. As a result, the total land holding size of small-scale operations decreased in 2017. Small-scale farmers are subsistence farmers and mainly cultivate cereal crops such as sorgum, millet and maize.

3.4. Gambella National Park LULCC

Around 5,700 km^2 of the Gambella region is covered by Gambella National Park (GNP). However, currently there is new boundary which covers around 4,350 km^2 and is shifted towards the south western parts of the region (as shown in Fig. 4). It also means that the GNP would lose about 1,500 km^2 or about 25% tropical grassland cover of its area.

https://doi.org/10.1016/j.heliyon.2018.e00919

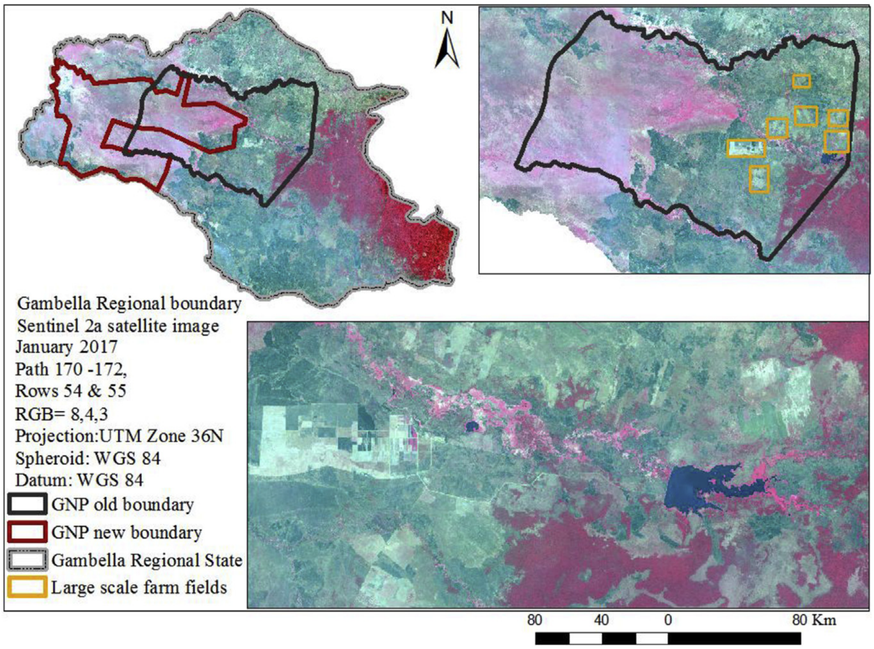

Fig. 4. The old and new proposed Gambella National Park boundary (top left) and rectangles enclosing large-scale commercial farm fields within the present GNP boundary from Sentinel 2a satellite image 2017 (top right) and zoomed out large-scale commercial farm fields within the old GNP boundary from Sentinel 2a satellite image 2017 (below).

Changes in LU/LC categories within the old GNP showed that areas of approximately 672 km^2, 761 km^2 and 725 km^2 were covered by farm fields in 1987, 2000 and 2017 respectively. As shown in Fig. 5, forest cover has increased from 250 km^2 in 1987 to 394 km^2 in 2000. However, by 2017, forest cover had decreased to 211 km^2. In addition, tropical grasslands, which covered an area of 3,385 km^2 in 1987, decreased to 2,584 km^2 in 2000 and 1,887 km^2 in 2017. Man-made structures, such as settlements, expanded from about 7 km^2 in 1987 to 101 km^2 in 2000, although they have since decreased to 37 km^2 by 2017. Within the new proposed GNP boundary, however, both agricultural activities and artificial areas are to be restricted. Abandoned farming activities and artificial areas within the new GNP will have the greatest chance of being incorporated into the GNP ecosystem. In the new GNP boundary (as illustrated in Fig. 6) the farmland cover was 19 km^2 and 60 km^2 in 1987 and 2000 respectively. However, in 2017 the farmland cover had decreased to 51 km^2. In addition, in 2017 within this new proposed boundary, 920 km^2 are under barren or sparsely vegetated land, while 378 km^2 are under tropical grasslands and 2,970 km^2 are wetland vegetated areas. In general, the expansion of wetland vegetated areas in the new proposed boundary has had a positive impact on wildlife conservation and on the ecological management of the park [39].

https://doi.org/10.1016/j.heliyon.2018.e00919

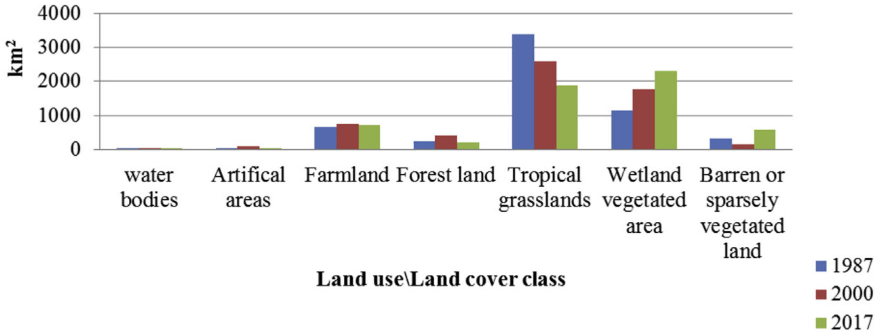

Fig. 5. Changes in the composition of Gambella National Park LU/LC categories in the old GNP boundary (1987, 2000 and 2017).

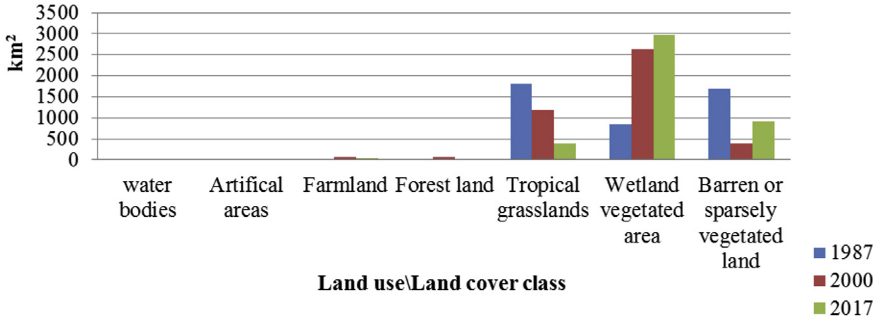

Fig. 6. Changes in the composition of Gambella National Park LU/LC categories in the new proposed boundary (1987, 2000 and 2017).

4. Discussion

The supervised classification of multi-temporal satellite images is an effective tool to quantify current LU/LC, as well as to detect changes in a changing environment [32]. The study reveals that in the last three decades, tremendous LULCC have been observed in the Gambella region. These LULCC have been caused by a mixture of climatic factors and strong human interference and have impacts on both the natural environment and on people’s livelihoods.

The observed trend of expanding agricultural area in Gambella region between 1987 and 2017 is supported by Ethiopian government, since large-scale land investment is an important part of its development strategy [40]. In the 1980s, the previous Ethiopian government, Derg, introduced large state farms in the region. However, in 1991, the state farms collapsed and the farmland was abandoned after the abolition of the Derg government [41]. Since the mid-2000s, however, the Ethiopian People’s Revolutionary Democratic Front (EPRDF) have handed over previously state-owned farmlands to foreign companies [42]. As a result, large-scale farming activities have expanded rapidly in the Gambella region within a short period of time.

https://doi.org/10.1016/j.heliyon.2018.e00919

According to the Ethiopian Investment Agency's official report, from 2004 to 2015 around 185 investors were granted licence to invest in the Gambella region, out of which 22 were foreign investors and the remainder were local investors [43]. By 2008, in Gambella alone, MOARD made around 47% or 1.1 million ha of suitable farmland available to large-scale farm companies. Nevertheless, MOARD asserted that while some of the investors are operating their lands wisely the majority are leaving their lands barren and uncultivated. Large-scale commercial farmland expansion threatens the land rights and livelihoods of indigenous communities, and nowadays their land is given for cash crop/monocrop production. For instance, in 2012, the Ethiopian government removed/relocated more than 70,000 indigenous people as a result of large-scale commercial farming activities [12, 44]. This relocation/resettlement has had a negative impact on small-scale farmland expansion. In the past three decades, small-scale farmland increased by just 29 km^2, or 1.5%. Although the Central Statistics Agency (CSA) report indicated that population between 2007 and 2015 in Gambella region was increasing at around 4.15% per year, small-scale farmland expansions to meet short-term survival rates are insignificant. According to a World Bank report [34], the average land holding size per family in the study area is 1.4 ha, which is less than the average standard land holding size of 2 ha, recommended by the Food and Agriculture organization (FAO) [45]. Land holding size, land/property rights and food insecurity are therefore the major concerns of small-scale farmers [45, 46]. Since the 2010s, land conflicts and clashes between the two major ethnic groups (Anyuaa and Nuers) have largely increased in the region over farmland [47].

The Oakland Institute (2011) conducted a study on the impact of large-scale agricultural investment on local people's livelihoods and LULCC in Gambella Regional State. The findings reveal that investors cleared huge areas of forest by practising the slash-and-burn farming system in their fields [48]. This is the greatest threat to forest cover, which is the main source of food for the hunter-gatherer indigenous peoples [13]. In 1987, the total forest cover was 4,188 km^2; however, in 2000 there was neither state nor large-scale farming investment in the region. As a result, the forest cover increased to 4,524 km^2. This study also confirmed that the forest cover and large-scale agricultural investment has an indirect/inverse relationship. For instance, forest cover declined when large-scale farm investment was restarted in the region in the mid-2000s and this implies that about 576 km^2 of forest land has disappeared between 2000 and 2017. Recent statistics also indicate that the annual deforestation rate in Ethiopia in general is about 1,410 km^2 per year [49] due to farmland expansion. With this pace of deforestation, the unique forest cover of the Gambella region, with its rich biodiversity, will have disappeared by approximately 2133. This would have a significant impact on the LU/LC ecology and biodiversity through the whole Gambella region.

https://doi.org/10.1016/j.heliyon.2018.e00919

On the other hand, in 2003, the FDRE established a revitalisation of population relocation strategies of the resettlement and villagisation (R&V) programme. This programme resurrected the problems last seen during the Derg regime. As a strategy of transforming the livelihood of settlers and ensuring food security by providing socio-economic and infrastructural delivery, it is a voluntary principle through an intra-regional approach. Since the mid-2000s, scattered households have been collected together into selected nucleated villages in order to improve their access to social, economic and administrative services in the Gambella region. As a result of this, farmers had to leave their ancestral farmlands and relocate to villages. Thus, according to our findings, about 1,381 km^2 of farmland has been abandoned and re-converted into tropical grasslands because of the R&V programme. In the past, a poorly planned resettlement programme leading to uncontrolled encroachments has caused great damage to the vegetation composition and structure of the area [11]. For instance, resettlement sites were established in the 1980s by clearing dense natural forests.

Our results show that there are strong human interferences within the old boundaries of the national park, as seen e.g. by the farming activities and the decrease of forest land, while within the new boundaries, almost no farming activities were observed in 2017 and also less artificial areas exist in the new boundaries. However, the new boundaries of GNP contain less forest land than in the old boundaries. Besides LU change, we identified large areas of LC change within both, the old and the new boundaries of the GNP. Over 1.498 km^2 of natural grassland has been transformed mainly into wetlands over the last decades. Several studies support our findings within the GNP and identify possible reasons for this development. According to [39] the changes are not only driven by natural processes, but mainly due to human interferences, such as unsustainable utilization of natural resources such as deforestation, commercial farm expansion, and settlement/encroachment, and wild fires. Since the 1990s, the government's land allocations to external agribusiness investors in and around the GNP has threatened the livelihoods of local communities [50], and currently the pristine areas of the park are shrinking and suffering widespread damage to plant species and wild animals [51]. The clearing of land and large-scale deforestation has increased competition for land between investors and local farmers. All these syndromes contradict the idea of a protected area and caused social and economic hardship [11].

Since 2015, the Ethiopian government has proposed a new park boundary to make the park more suitable for wildlife conservation and ecosystem management [52]. As result, the government is restricting encroachment/settlement and large-scale/commercial farming activities within the new GNP boundary. Recently, the national park has also had the support of foreign-funded programmes, which is taking part in the setting up of a land use plan for the Gambella region [53].

https://doi.org/10.1016/j.heliyon.2018.e00919

5. Conclusion

From the overall research findings, some important conclusions can be drawn. Remote sensing has an outstanding value as an independent and objective source of information on LULCC. In the Gambella resettlement program, demographic growth and large-scale land investment has caused social and environmental impacts, as forests are cleared and communities are displaced, or lose access to farmland, forest or water resources. Particularly, large-scale land investment without proper environmental impact assessments and unplanned resettlement programmes were the cause of enormous LULCC in the Gambella region. Failed resettlement programmes in the 1980s and R&V in the mid-2000s led to the re-establishment of grasslands that are important for a rewilding process in the region, which is unique in Ethiopia. This rewilding process in the Gambella region is able to allow indigenous plant species to grow on their own and produce new generations without human intervention.

The results of this research revealed the existence of significant LULCC over the last 30 years. The observed changes varied from one LULCC category to another. This study showed that the expansion of large-scale commercial farmland increased in 2017 compared to 1987. The expansion of small-scale farmland between 1987 and 2017, on the other hand did not show any significant change, and it is less than 2% area change unless one would expect a higher increase to a massive population growth. This shows the dominant influence of commercialisation on agriculture in the region. In addition, barren land has increased considerably during the last two decades. On the other hand, tropical grassland and forest areas are declining at a rapid pace.

The GNP, which is the nation's largest national park ecosystem has also been affected by LULCC. The conversion of tropical grasslands and forest land to large-scale farmland has caused varied and extensive environmental degradation in the GNP, and major negative outcomes for local people's livelihood. For instance, the establishment of the new park boundaries resulted in a loss of large parts of the wetland vegetated area and water bodies. Identifying the complex interaction between changes and its drivers over time is significant in determining future change, setting up decision-making mechanisms and constructing alternative scenarios. Therefore, in future, sustainable development LU/LC has to be monitored at regular intervals and an integrated LU policy is required.

In general, this study advocates the use of multi-temporal and high-resolution satellite data to detect and assess changes in LU/LC comprehensively. Only local field work and the compilation of additional sources can enable the observed changes to be put into a larger perspective, and to be able, finally, to understand the LU/LC dynamics in the Gambella region. This is a necessary prerequisite to formulating

https://doi.org/10.1016/j.heliyon.2018.e00919

successful LU strategies required for the appropriate and sustainable development of the study area.

To sum up, this paper has documented LULCC in the Gambella region of Ethiopia. It quantifies the changes and illuminates reasons and effects. The Gambella region is among the least developed and the most fertile regions of Ethiopia. It has large natural reserves in terms of pristine forests, wetlands, tropical grasslands and biodiversity. At the same time, its future development potentials are large and based on solid indicators like available rainfall, fertile soils and accessible land. Although all documented LULCC during the last decades point towards the usual conversion of natural land into human utilisation, one may also conclude that Gambella region is still far away from a terminal stage of human interference. This opens up the chances to develop and implement policies to ensure the sustainable future development of the Gambella region. It should enforce non-interference into the new GNP boundary in order to protect the remaining pristine areas, develop smallholder agriculture towards larger yields to raise income and at the same time preserve natural areas of wetland and grassland. In addition, large-scale farming should be slowed down and should demonstrate sustainable operations with respect to, e.g. erosion and pollution.

Declarations

Author contribution statement

Azeb W Degife: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Florian Zabel, Wolfram Mauser: Conceived and designed the experiments; Analyzed and interpreted the data; Wrote the paper.

Funding statement

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Competing interest statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

https://doi.org/10.1016/j.heliyon.2018.e00919

References

[1] Ankana, Land and forest management by land use/land cover analysis and change detection using remote sensing and GIS, J. Landsc. Ecol. 9 (2016).

[2] E.F. Lambin, P. Meyfroidt, Global land use change, economic globalization, and the looming land scarcity, Proc. Natl. Acad. Sci. Unit. States Am. 108 (9) (2011) 3465–3472.

[3] L. Cotula, Land Rights and Investment Treaties: Exploring the Interface, International Institute for Environment and Development, 2015.

[4] A.K. Braimoh, M. Osaki, Land-use change and environmental sustainability, Sustain. Sci. 5 (1) (2010) 5.

[5] S. Ganugapenta, J. Nadimikeri, L.P. Tella, Landuse and landcover analysis using remote sensing and GIS: a case study in and around Rajampet, Kadapa District, Andhra Pradesh, India, IJMRD 2 (1) (2015) 186–191.

[6] M.K. Tiwari, A. Saxena, Change detection of land use/landcover pattern in an around Mandideep and Obedullaganj area, using remote sensing and GIS, Int. J. Technol. Eng. Syst. 2 (3) (2011) 398–402.

[7] M. Muke, B. Haile, Land-use/cover change analysis using remote sensing techniques in the landscape of Majang Zone of Gambella Region, Ethiopia, Afr. J. Environ. Sci. Technol. 12 (4) (2018) 141–149.

[8] D. Rahmato, Land to Investors: Large-scale Land Transfers in Ethiopia, African Books Collective, 2011.

[9] Gebre Brhane Meles, Andualem Zemenu Awoke, Impacts of resettlement on land use land cover changes and natural vegetation conservation practices of resettlers in Abobo Woreda, Gambella, Ethiopia, J. Resour. Dev. Manag. 40 (2018) 20–28.

[10] B.T.T.M. Zemenu Awoke, Impacts of resettlement on woodland degradation in Abobo Wereda, Gambella, Ethiopia, World J. Pharm. Life Sci. 2 (2016) 60–77.

[11] A.A. Eshetu, Forest resource management systems in Ethiopia: historical perspective, Int. J. Biodivers. Conserv. 6 (2) (2014) 121–131.

[12] F. Horne, L. Bader, Waiting Here for Death: Forced Displacement and "Villagization" in Ethiopia's Gambella Region, Human Rights Watch, 2012.

[13] O. Othow, S. Gebre, D. Gemeda, Analyzing the rate of land use and land cover change and determining the causes of forest cover change in Gog

https://doi.org/10.1016/j.heliyon.2018.e00919

District, Gambella Regional State, Ethiopia, J. Remote Sens. GIS 6 (218) (2017) 2.

[14] G. Chimdesa, The political economy of deforestation and forest degradation in Ethiopia: review article, J. Resour. Dev. Manag. 29 (2017) 38–43.

[15] M. Tadesse, Gambella the Impact of Local Conflict on Regional Security, Institute for Security Studies (ISS), Addis Ababa, 2007.

[16] UNICEF, Gambella Regional Briefing Note, UNICEF, Ethiopia, 2016.

[17] A. Sewonet, Breaking the cycle of conflict in Gambella Region, in: Assessment Mission, United Nation, Addis Ababa, 2002, pp. 23–29.

[18] M. Kottek, et al., World map of the Köppen-Geiger climate classification updated, Meteorol. Z. 15 (3) (2006) 259–263.

[19] Climatedata, Climate Gambela – Ethiopia, 2014 [cited 2018 17/05]; Available from: https://www.climatedata.eu/climate.php?loc=etzz0024&lang=en.

[20] Y. Alemayehu, H. Gebrekidan, S. Beyene, Pedological characteristics and classification of soils along landscapes at Abobo, southwestern lowlands of Ethiopia, J. Soil Sci. Environ. Manag. 5 (6) (2014) 72–82.

[21] A.W. Degife, W. Mauser, Socio-economic and environmental impacts of large-scale agricultural investment in Gambella Region, Ethiopia, J. US China Publ. Adm. 14 (4) (2017) 183–197.

[22] F. Zabel, B. Putzenlechner, W. Mauser, Global agricultural land resources – a high resolution suitability evaluation and its perspectives until 2100 under climate change conditions, PloS One 9 (9) (2014) e107522.

[23] J. Rawat, M. Kumar, Monitoring land use/cover change using remote sensing and GIS techniques: a case study of Hawalbagh block, district Almora, Uttarakhand, India, Egypt. J. Remote Sens. Space Sci. 18 (1) (2015) 77–84.

[24] USGS, Landsat and Sentinel 2a Higher Level Science Data Products, United States Geological Survey, Virginia, United States, 2017.

[25] S.A. Boyle, et al., High-resolution satellite imagery is an important yet underutilized resource in conservation biology, PloS One 9 (1) (2014), e86908.

[26] M. Boori, V. Vozenilek, Remote sensing and land use/land cover trajectories, J. Geophys. Rem. Sens. 3 (2014) 123.

[27] M. Hasmadi, H. Pakhriazad, M. Shahrin, Evaluating supervised and unsupervised techniques for land cover mapping using remote sensing data, Geogr. Malays. J. Soc. Space 5 (1) (2017).

 https://doi.org/10.1016/j.heliyon.2018.e00919

[28] H. Alphan, H. Doygun, Y.I. Unlukaplan, Post-classification comparison of land cover using multitemporal Landsat and ASTER imagery: the case of Kahramanmaraş, Turkey, Environ. Monit. Assess. 151 (1) (2009) 327−336.

[29] J.A. Richards, Clustering and unsupervised classification, in: Remote Sensing Digital Image Analysis: an Introduction, Springer Berlin Heidelberg, Berlin, Heidelberg, 2013, pp. 319−341.

[30] A. Butt, et al., Land use change mapping and analysis using remote sensing and GIS: a case study of Simly watershed, Islamabad, Pakistan, Egypt. J. Remote Sens. Space Sci. 18 (2) (2015) 251−259.

[31] R.P. Gupta, Remote Sensing Geology, Springer Science & Business Media, 2013.

[32] M.C. Cheruto, et al., Assessment of land use and land cover change using GIS and remote sensing techniques: a case study of Makueni County, Kenya, J. Remote Sens. GIS 5 (4) (2016) 1−6.

[33] W.M.S. James Keeley, Eid Abdurehman, Lokeley Admasu, Large-scale Land Investment in Ethiopia: How Much Land Is Being Allocated, and Features and Outcomes of Investments to Date, International Institute for Environment and Development (IIED), Addis Ababa, 2013.

[34] CSA, World Bank, Ethiopia Rural Socioeconomic Survey (ERSS), Central Statistical Agency, Addis Ababa, 2013.

[35] National Climatic Data Center, Weather Data, Photius Coutsoukis and Information Technology Associates, 2017.

[36] A.M. Dias, State and Societal Challenges in the Horn of Africa: Conflict and Processes of State Formation, Reconfiguration and Disintegration, Centro de Estudos Internacionais, Lisboa, 2017, p. 170.

[37] H. Verhoeven, Black Gold for Blue Gold? Sudan's Oil, Ethiopia's Water and Regional Integration, 2011.

[38] USAID, Ethiopia Drought/Famine Fiscal Years 1985-1986, in Final Disaster Report, 1987.

[39] T.S.a.S.B. Abreham Berta, Carbon stock potentials of Gambella National Park: implication for climate change mitigation, Adv. Life Sci. Technol. 35 (2015) 41−55.

[40] J. Keeley, et al., Large-scale Land Deals in Ethiopia Scale, Trends, Features and Outcomes to Date, Full Spectrum Print Media, London, 2014, p. 62.

https://doi.org/10.1016/j.heliyon.2018.e00919

[41] W. Crewett, B. Ayalneh, B. Korf, Land Tenure in Ethiopia Continuity and Change, Shifting Rulers, and the Quest for State Control, International Food Policy Research Institute (IFPRI)., Washington, DC, 2008.

[42] T. Gebeyehu, Poverty, peasantry and agriculture in Ethiopia, Ann. Agrar. Sci. 15 (2017) 420−430.

[43] Ethiopian Investment Agency (EIA), List of Licensed All Investment Projects (Agriculture Sector in Gambella Region) since March 25, 1993 - December 25, 2015 G.C., Ethiopian Investment Commission, Addis Ababa, 2016.

[44] E. Fratkin, Ethiopia's pastoralist policies: development, displacement and resettlement, Nomadic Peoples 18 (1) (2014) 94−114.

[45] G. Rapsomanikis, The economic lives of smallholder farmers; an analysis based on household data from nine countries, in: Food and Agriculture Organization, Food and Agriculture Organization, Rome, 2015.

[46] A. Gebre-Selassie, T. Bekele, Global growing casebook: insights into African agriculture, in: D.K.-R.J.P. Christoph Eder (Ed.), A Review of Ethiopian Agriculture: Roles, Policy and Small-scale Farming Systems, European Commission: Global Growing Campaign, 2012, pp. 36−65.

[47] S.A. Mamo, When large-scale land acquisition meets local conflict: experiences from Gambela Regional State, Ethiopia, Int. J. Multicult. Multireligious Underst. 4 (4) (2017) 1−14.

[48] Oakland Institute, Understanding Land Investment Deals in Africa Country Report: Ethiopia, The Oakland Institute, Oakland, CA, 2011, p. 53.

[49] M. Hailesellassie, Global Forest Resources Assessment 2010 Country Report Ethiopia, NRMD, Rome, 2010.

[50] D.R. Tom Blomley, Nelson Fred, Flintan Fiona, 'Land Grabbing': Is Conservation Part of the Problem or the Solution?, 2013. London.

[51] A.B. Aneseyee, Vegetation composition and deforestation impact in Gambella National Park, Ethiopia, J. Energy Nat. Resour. 5 (3) (2016) 30−36.

[52] FDRE, Council of ministers regulation to provide for the designation of Gambella National Park, in: Federal Negarit Gazette, Berhanena Selam Printing Press, Addis Ababa, 2015, pp. 7989−7998.

[53] D. Ambrosetti, Climatic and Environmental Challenges: Learning from the Horn of Africa, Centre français des études éthiopiennes, Addis Ababa, 2016.

 https://doi.org/10.1016/j.heliyon.2018.e00919

Publication II

Degife, A. W., F. Zabel and W. Mauser (2019). "Land Use Scenarios and Their Effect on Potential Crop Production: The Case of Gambella Region, Ethiopia." Agriculture 9(5): 105.

Land Use Scenarios
and Their Effect.pdf

.

agriculture

MDPI

Article

Land Use Scenarios and Their Effect on Potential Crop Production: The Case of Gambella Region, Ethiopia

Azeb W. Degife *, Florian Zabel and Wolfram Mauser

Department of Geography, Ludwig-Maximilians-Universität München, 80333 Munich, Germany; f.zabel@lmu.de (F.Z.); w.mauser@lmu.de (W.M.)

* Correspondence: a.degife@iggf.geo.uni-muenchen.de; Tel.: +49-89-2180-6695

Received: 19 April 2019; Accepted: 5 May 2019; Published: 10 May 2019

check for updates

Abstract: Agricultural intensification and cropland expansion are the key policies to increase food production in Ethiopia. Gambella is one of the regions in Ethiopia which is highly suitable for agriculture; however, the local people still face food shortages. We therefore investigated the potential for intensification and cropland expansion. In this study, we developed land use scenarios of agricultural intensification and expansion and analysed their effect on potential crop production in the region and estimated the population that could be nourished as a result. We distinguished between different degrees of intensification, ranging from low input rainfed to high input irrigated agriculture and different degrees of expansion, considering the best 30% or 50% of land to be utilized for expansion. While the results reveal that irrigation had almost no effect on potential yields, they also show that the potential calorie production in all scenarios far exceeds the current and possible future caloric requirements of Gambella's population. For example, for the top 50% expansion scenario, calorie production increased by +428% for the low input and by +1092% for the high input scenarios. Thus, Gambella could nourish up to 21 million people and serve as a bread basket for the entire country, which could improve national food security.

Keywords: cropland expansion; Gambella region; intensification; land use scenarios

1. Introduction

According to World Population Review, the total population of Ethiopia in 2018 was about 108 million. With an annual growth rate of 2.46% [1,2], this number is expected to grow to 174 million by 2050 [2]. Population growth is outpacing agricultural production in Ethiopia [3] and domestic food production has failed to meet the food requirements of the country [4]. The annual food deficit increased from about 0.75 million tons in 1979/80 to 1.4 million tons in 2000 [5]. A series of production failures has resulted in chronic food insecurity since the 1980s and adequate food production has been a serious problem in the country for decades [4,6]. According to the UN, Ethiopia has been the largest recipient of food aid among Sub-Saharan African countries [6]. FAO's 2010 report indicated that 5.2 million people in Ethiopia face an uncertain food security situation [7].

Smallholders account for 96% of the total area cultivated in Ethiopia [8,9]. They generate the major share of the total production of the main crops. Teff, wheat, maize, sorghum and barley are the five major cereal crops in Ethiopia, accounting for about three-quarters of the total area cultivated and 29 percent of agricultural Gross Domestic Product (GDP) in 2005/06 (14 percent of total GDP) [9]. However, the Ethiopian population is still undernourished; underscoring the importance of increasing domestic food productivity [10]. One of the greatest challenges for Ethiopia therefore is to meet society's growing food needs whilst reducing the environmental impact of agriculture. The government of Ethiopia has established several programs to address the issue, yet recurring droughts and the population's heavy dependence on rain-fed agriculture, which is plagued by low productivity levels, present ongoing challenges for food production [11]. Among the several options that have been discussed to meet future food demand globally [12], there is agreement that increased production is the answer, which can be achieved by (1) intensification and (2) agricultural land expansion [13–16]. A combination of two options will most likely be chosen to meet the challenge: increasing yields through agricultural intensification on existing cropland and increasing production through cropland expansion. Both options have an impact on the environment and society and should be balanced out carefully to identify the best solution. Over the past four decades, increase in crop production in most parts of Ethiopia has occurred predominantly through cropland expansion [17]. However, of late yield increase and intensification rather than area expansion has been the major source of growth in agricultural output in the country [14].

In this paper, we focus on intensification and potential cropland expansion for future agricultural crop production in Gambella National Regional State, which is one of the regional governments forming the Federal Democratic Republic of Ethiopia. The region is endowed with highly diversified natural resources, in particular the large expanse of arable land, rainfall and ground water resources, which render the region best suited for cropland expansion and agricultural development [18]. Despite this "abundance", livelihoods and subsistence farming in the region are still deeply marked by a strong vulnerability to food shortage and large yield gaps [19]. Land fragmentation, farmer's traditions and beliefs, pests, post-harvest management and losses, institutional practices/norms and policy, farmers' resistance to new technology, weak linkages among public, private and non-governmental extension staffs, lack of crop management with respect to planting time and weed control and low usage of organic or mineral fertilizers are the main causes of low productivity and high yield gaps in the region [10,20–24]. We quantify crop yield gaps in the Gambella region and address the related challenges in the interest of increased and sustainable crop production in the region [22]. Although reference/actual yields are documented, there is a lack of insightful statistics and estimates on current yield gaps of the main crops. This information is a prerequisite for developing the region through sustainable intensification and/or expansion of agriculture. We therefore hypothesize that the potential in the Gambella region is huge to increase crop productivity and to improve efficiency of use of the natural resources (water, soil and climate) to meet the growing demand for food in the region and in Ethiopia.

The purpose of this paper is to estimate the magnitude and extent of intensification potential of the key Gambella cereal crops (maize and sorghum) and to identify potential cropland expansion areas in the region. The specific objectives of this paper are: (1) to estimate crop yield gaps and potential production by comparing simulations of potential crop yield and the average reference data/actual achieved crop yields from 1997–2017. Closing yield gaps aims not only at increasing crop yield and production but also at improving the efficiency of land, water and labour use, at reducing production costs and at increasing sustainability through, for example, reduced erosion and increased water use efficiency; (2) to assess potential areas (hot spots) for productivity gains and to identify what percentage of land is needed to accommodate cropland expansion in a manner consistent with sustainable food production and conservation of nature in the future (excluding Gambella National Park, artificial areas, water bodies, wetland and forest land).

Our motivation in this regional study is to give specific insight for scientists, policymakers, local farmers and various stakeholders in the agriculture sectors to overview the potential crop production of the region in a spatially explicit way in high detail, to identify regions where a realization of potentials should be prioritized in the context of region-specific socio-economic conditions through targeted development and to quantify the prospective/capacity of the potential food production of the country and the region.

2. Materials and Methods

Intensification potential related with closing yield gaps and agricultural expansion that are based on country or state level empirical data usually neglect spatial heterogeneous distribution of biophysical constraints for crop growth, which are determined by, for example, soil, climate and topography. Additionally, empirical quantifications of potential yields often use maximum farmer yields that usually underestimate yield potentials, especially in regions with high yield gaps, such as the Gambella region [25–27]. Thus, combined potentials of intensification and expansion should rely on spatially distributed crop growth models (e.g., gridded). These can be used to simulate potential crop growth for a range of scenarios for all locations in the considered region (even the ones which are not currently under agricultural use) [28]. The scenarios should cover a realistic spectrum of varying management practices like nutrition levels, pest mitigation measures and irrigation intensities, as well as different expansion strategies with respect to where to expand and how much. The resulting spatial simulation results for the different scenarios are compared and the potential as well as the related consequences are documented for each scenario. This paper develops a general framework of intensification/expansion scenarios, which can be used for a broad range of geographical regions in the tropics, for which intensification and expansion of agriculture have to be balanced in order to strengthen food security. The framework is applied to the Gambella region in Ethiopia as a case study to demonstrate its viability.

The framework is shown in Figure 1. Expansion considers only those areas which are (1) feasible with respect to, for example, not being protected areas or biodiversity hot spots and (2) non-agricultural areas to begin with, which show the highest yield potential. Two alternative expansion scenarios are assumed in the study: (1) expansion takes place in the highest yielding 30% (TOP 30) and (2) 50% (TOP 50) of the feasible rangeland in the area. They assume that expansion takes place in the highest yielding 30% and 50% of the feasible rangeland in the area. As illustrated in Figure 1, parallel to these two expansion scenarios we develop three intensification scenarios, which reflect different intensification options ranging from low input rainfed agriculture through high input rainfed agriculture to high input irrigated agriculture. The combination of the assumptions in expansion and intensification leads to 6 scenarios: Low Input Rain-fed (LIR 30 and LIR 50), High Input Rain-fed (HIR 30 and HIR 50) and High Input Irrigated (HII 30 and HII 50) (Figure 1). For all 6 scenarios, we estimate potential yields (t/ha) and production (t/season), calorie production (reference/actual and potential) and the number of people that can be nourished from the calorie production in the region, based on global average calorie intake.

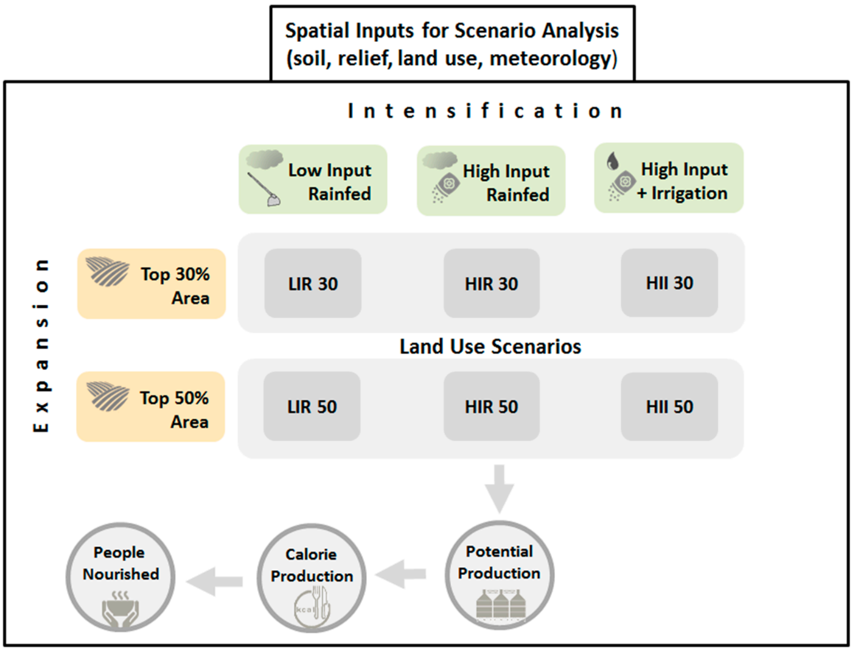

Figure 1. Conceptual framework: Spatial land use scenarios based on assumptions for expansion (brown boxes) and intensification (green boxes). Derived outputs are potential crop- and calorie production and number of people nourished. The scenarios are simulated and analysed spatially, based on spatial information on soil, relief and meteorological drivers.

2.1. Study Area

Gambella National Regional State has been chosen as a regional example to demonstrate the feasibility of the framework. It is situated in the south-western part of Ethiopia, with a total land area of 25,521 km^2. It shares a long border with South Sudan and two other Ethiopian regions: Oromia to the north and east and the Southern Nations, Nationalities and Peoples' Regional State (SNNPRS) to the south (as shown in Figure 2). Altitude in the region progressively declines from the east to the west, with parts of the region ranging from 1000 to 2200 m above mean sea level in the east, to 500–900 m in the centre and 300–500 m in the west [29]. Around 90% of the region is dominated by lowland area [30]. Temperature and rainfall of the region are conducive for agricultural activities. As shown in Figure 3, the annual rainfall ranges between 800 and 1200 mm and 85% of rainfall occurs between May and October [31]. The mean annual temperature of the region varies from 17.3 to 28.3 degrees Celsius (°C) [32].

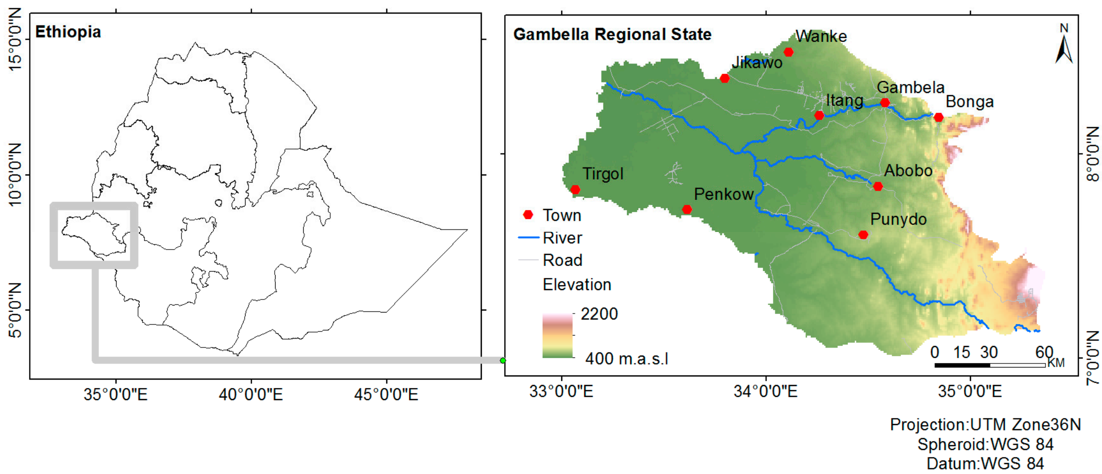

Figure 2. Gambella Locational Map: Federal Democratic Republic of Ethiopia (left) and Gambella Regional State (right).

Gambella National Regional State is one of the Ethiopian regions rich in water resources. The major rivers are the Baro, Akobo, Alwero and Gillo. All of these rivers have major tributaries and are large enough for the local population to depend on, as far as present and future irrigation needs are concerned [33]. Gambella regional state reports indicate the development of first irrigation schemes with total irrigated area of 1315 hectares (ha), out of which 415 ha are from small-scale and 900 ha are from medium scale farms [34]. The rivers originate in the Ethiopian highlands (2000–3500 m) situated in the east of the area and fall to the Gambella plain (450 m) in the west [28]. The annual potential evapotranspiration in the region reaches about 1612 mm, with the maximum value occurring in March (212 mm) [32]. According to the 2017 Ethiopian population projection, Gambella is sparsely populated, the total population of the region being approximately 436,000 [35].

Land and water are key resources for the livelihood of the people living in the region [33]. The natural resources make the region potentially an ideal area for both commercial and small-scale farming and therefore for intensification and expansion both by commercial and small-scale farmers. The Ethiopian government has identified Gambella region as one of the regions in Ethiopia suitable for agricultural investments [36–38] and has classified most parts of the area in the region as under-exploited (under-utilized) [39], having a potential for agricultural production. Despite its huge natural resources potential and opportunities [19], the region is one of the poorest in the country [40]. Currently, the livelihood of the region is mainly derived from subsistence agriculture. Flood recession agriculture is common, particularly maize and sorghum, being widely practiced by local people along the rivers [41] and these two crops supply over 70% of average daily caloric intake in the region [42].

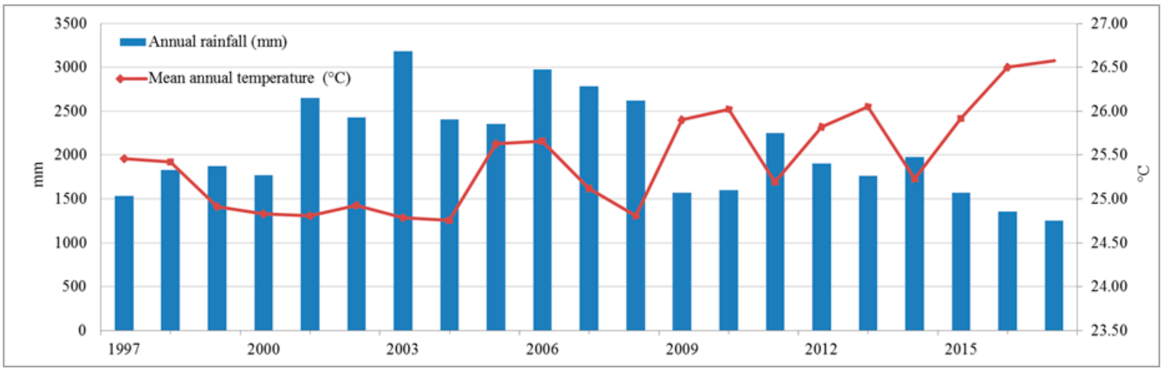

Figure 3. Gambella National Regional State average annual rainfall (mm) and mean annual temperature (°C) (1997–2017) from ERA-interim reanalysis data-set.

2.2. Reference Data

The reference yield or actual yield statistics (YA) is defined as the typical average yield of the farmers [43]. We used reference data on yield and harvested area obtained from the Ministry of Agriculture (MOA) and the National Agricultural Statistic Service, Ethiopia's annual Agricultural Sample Survey (AgSS) and Ethiopia's Central Statistics Authority (CSA), which provides critical information on small-scale farmer reference/actual crop yields and management practices for maize and sorghum from 1997 to 2017 at the regional level. Moreover, we used several additional sources of information such as localized agricultural information from the Gambella Regional Bureau of Agriculture.

2.3. Simulation of Potential Yields

One of the common crop modelling applications is the estimation of potential productivity under different assumptions of biophysical constraints [44]. We use the model (PROMET) (Processes of Mass and Energy Transfer [27,45]). PROMET is an agro-hydrological land surface process model, which contains a mechanistic, bio-physical, dynamic vegetation component to model crop growth and yield formation [46,47]. PROMET allows spatially distributed, raster-based simulations, which model net primary production, evapotranspiration, water balance and yield at different scales, from field to global, as a function of meteorological drivers as well as soil and terrain information. PROMET determines and considers water availability through soil moisture balance, radiation balance and the physiological regulation mechanisms of plant canopies [47,48]. The dynamic crop growth component uses parameters, which represent the sensitivity of the crops to environmental conditions (e.g., temperature, soil suction, nutrient supply) and which determine phenological development and crops reactions to related stresses. Management practices such as crop cultivar selection, sowing date, harvest date and fertilization levels are considered [45]. PROMET is well parameterized and validated for (but not restricted to) the simulation of the two important Gambella cereal crops, maize and sorghum (see, e.g., Reference [27]). The required parameters for this paper were either derived from the literature [49] or determined through comparison with recorded yields in different parts of the globe. The spatial nature of PROMET also allows localizing the potential of cropland expansion through considering biophysical drivers at the local scale, such as climate, soil quality and topography. Simulation of potential yields outside the actual cropland allows determining where an expansion of cropland would potentially be most feasible under the given natural conditions.

The model takes into account the spatial heterogeneity of the study area with reference to climate, soil and terrain conditions. We simulate the potential agro-ecological yields of the selected crops for all agriculturally suitable and feasible geographical locations in Gambella region. In this paper we have defined yield potentials (YP) as theoretically optimum yields that can be achieved with certain assumptions on crop management. At each location in the region, optimal management creates a yield potential depending on the environment. Options can, for example, be assumed as rainfed agriculture or irrigated agriculture, no nutrition, low input nutrition or high input for a particular cultivar [43,50]. In our study we assume well adapted standard cultivars of maize and sorghum, optimal sowing and harvest dates and no harvest losses due to pests or diseases, as well as no further losses during transport or storage. For simulating the yield potentials for the 6 scenarios from Figure 1, we use different combinations of the mentioned management options. For each scenario, PROMET is run for the whole actual as well as the potential and feasible cropland in the Gambella region, with a spatial resolution of 30 arc seconds (approx. 940 × 940 m at the Equator). It is driven by meteorological inputs of the years 1997–2017, which are statistically downscaled from the 0.5 degree (approx. 50 km) ERA-Interim reanalysis data-set [51] to the model resolution. Soil data is derived from the Harmonized World Soil Database (HWSD) and topography from the SRTM (Shuttle Radar Topography Mission) data-set [27].

2.4. Land Use Scenarios

2.4.1. Expansion

This part is concerned with cropland expansion to improve the potential food production in the region. For this purpose, we developed a "TOP 30% cropland expansion" and a "TOP 50% cropland expansion" scenario on land conversion and expansion in the Gambella region. Both rest on an identified potential cropland of 1,436,500 ha (from our pervious land use land cover classification of the region (see, e.g., Reference [39]), we identified potential cropland). We consider Ethiopian land use regulations and legislation and exclude artificial areas, water bodies and protected areas according to the International Union for Conservation of Nature (IUCN) [52]. Accordingly, the Gambella National Park, forest land [53] and wetland vegetated areas [54] and current cropland are excluded from potential expansion areas. We assume in the scenario that agricultural expansion strategically follows a gradient from high to lower yield potentials. It is therefore assumed that expansion starts at the location with the highest potential and consecutively selects locations with the next lower potential. We further assume that not all possible expansion will take place, because investments have to take place and they have to be financed by a return that is diminishing with expansion because of decreasing yield potentials. We therefore define a TOP 30% and TOP 50% expansion scenario, where the best 30% (375,000 ha, high investment costs) and 50% (600,000 ha, lower investment costs) of potential farmland are used for cropland expansion. These expansion areas are identified by ordering the PROMET simulation results of each pixel according to their yield potentials and then selecting the corresponding best 30% and 50% pixels.

2.4.2. Intensification

Currently, around 280,000 ha of land in the Gambella region is covered by cropland. It consists of both small and large-scale farms. It is therefore unrealistic to assume that intensification can completely close current yield gaps, because of many factors which in practice work against it, such as severe weather and pests. We assume two scenarios for rainfed and irrigation, in which intensification closes the yield gap between the potential and the reference yield statistics by approx. 10% (LIR) and 40% (HIR and HII). A closure of yield gaps by 10% until 2050 corresponds to a continuation of current trends with average yield increases from 1997–2017 and can be considered "business as usual". We linearly regressed 20 years of crop yields to determine the average linear rates of yield improvement over the observed period. Many previous studies [55] have shown that crop yields increase linearly with time and we have used linear regression to project crop yields. We also close the yield gap by approx. 40% by assuming that the future agricultural outputs will follow a growth pattern which is similar to that of Ethiopia's current overall fast-growing economy. These considerations lead to three assumptions for intensification: low input rain-fed, high input rain-fed and high input irrigation.

- LIR scenario: we assume that intensification closes the yield gap between the potential and reference yield statistics by approx. 10% until 2050. However, we assume that there might be constraints to achieving potential production because of traditional ploughs, weak cooperatives and institutions, low technological development, less organized pest management or expensive pesticides, lack of a strong agricultural policy or economic institutions like leasing and no access to credit for the farmers. In general, in the LIR scenario we assume that "business as usual" continues until 2050.
- HIR scenario: we assume that intensification closes the yield gap between the potential and the reference yield statistics by approx. 40% until 2050. In the high input there is a large potential to increase rain-fed yields of maize and sorghum by increasing agricultural inputs through mechanization and fertilization and by improving infrastructure, education and governance.
- HII: we assume the same agricultural development as in high input rain-fed; however, in this case the water deficits of rainfed agriculture would be compensated through irrigation.

2.5. Reference Crop Calorie Production and Calorie Intake

In this paper we consider the 2 major food crops maize and sorghum. These crops account for 97% of Gambella region's crop production by small scale farmers and 95% of the region's harvested area [56]. We further assume that the current ratio of cultivated area of 50% maize and 50% sorghum will stay constant when closing yield gaps [57]. In order to convert reference/actual and potential production into meaningful information with respect to food security for the residents of Gambella and beyond, production has to be converted from mass into calories. We calculate the current small scale farmland crop calorie production for each crop (Ca) according to Equation (1) using the statistical data on the reference crop yield (Ya_r: rain-fed) and area harvested (H_r) and FAO's nutritive factors for converting crop mass into calories (f^i) [58,59] (Table S1). For both crops, calorie production under reference yield and yield gap closure scenarios was assessed based on the respective crop yield values (t ha^{-1}). The number of people that can be fed is assessed based on a global estimate of average daily per capita calorie consumption (2200 kcal/cap/day) [60].

$$Ca_r = \sum \left(Ya_r \times H_r \times f^i \right), \tag{1}$$

2.6. Simulations of Potential Crop Calorie Production and Calorie Intake

PROMET was run for the Gambella region on the actual and all potential and feasible cropland for the six selected scenarios for the period from 1997 to 2017, with a spatial raster grid of 30 arc seconds (approx. 940 × 940 m) resolution, to provide information on potential crop yields [45]. The extended simulation period of 20 years was chosen to be able to average yield potential over a large range of weather situations. We used PROMET data on potential yields for estimating the potential crop calorie production both for the current farmland and potential and feasible cropland. The potential crop yields are provided in t ha^{-1} in harvest weight, assuming common moisture content of harvested fruits, which is 12.75. The nutritive factor (f^i) is used to convert crop mass into crop calories. The crop production based on rain-fed and irrigated agriculture obtained by multiplying for each pixel in the simulation the high input potential yields (YP_r and YP_i, r: rain-fed, i: irrigated) and area harvested (H_r and H_i) provides the potential crop calorie production for high input levels (Ch) according to Equations (2) and (3). Finally, the crop calorie production values of 50% maize and 50% sorghum are added to get the total potential crop calorie production from the two crops and accordingly the number of people that can potentially be fed based on a global estimate of average daily per capita calorie consumption (2200 kcal/cap/day) [60].

$$Ch_r = \sum \left(YP_r \times H_r \times f^i \right), \tag{2}$$

$$Ch_i = \sum \left(YP_i \times H_i \times f^i \right), \tag{3}$$

To analyse the state of self-sufficiency of the population, we take the UN world population prospective report of 2017 [61]. It assumes that the total population of the region will roughly double from 436,000 in 2017 to around 880,000 in 2050.

3. Results

3.1. Land Use Scenarios' Effect on the Potential Yield from 1997–2017

As shown in Figure 4, potential yields are spatially highly variable due to more or less suitable climate and soil conditions for farming in the region. In general, rainfed potential yields (as shown in Figure 4A,C) decrease from high values in the north to lower values in the south of Gambella because of poor sandy Alisols in the south. The highest potential rainfed yields are simulated for both crops in the western highlands because of plenty of rainfall and reduced temperature stress. By selecting the current farmland from Figure 4 which closes the reference yield gap of maize and sorghum by 40%, the average potential yields on all possible and feasible cropland becomes 6.1 t ha^{-1} for maize and 2.7 t ha^{-1} for sorghum for the HIR intensification assumption and 6.4 t ha^{-1} and 2.8 t ha^{-1} for maize and sorghum respectively for the HII assumption (Figure 4B,D). The related simulations were also carried out for the LIR assumption by selecting the current farmland from Figure 4, which closes the reference yield gap of maize and sorghum by 10%, for the whole potential and feasible cropland. Here, the average potential yields of maize and sorghum are 1.5 t ha^{-1} and 0.7 t ha^{-1}, respectively. The CSA report shows that the average reference yield in Gambella region from 1997–2017 is 2.1 t ha^{-1} for maize and 1.1 t ha^{-1} for sorghum.

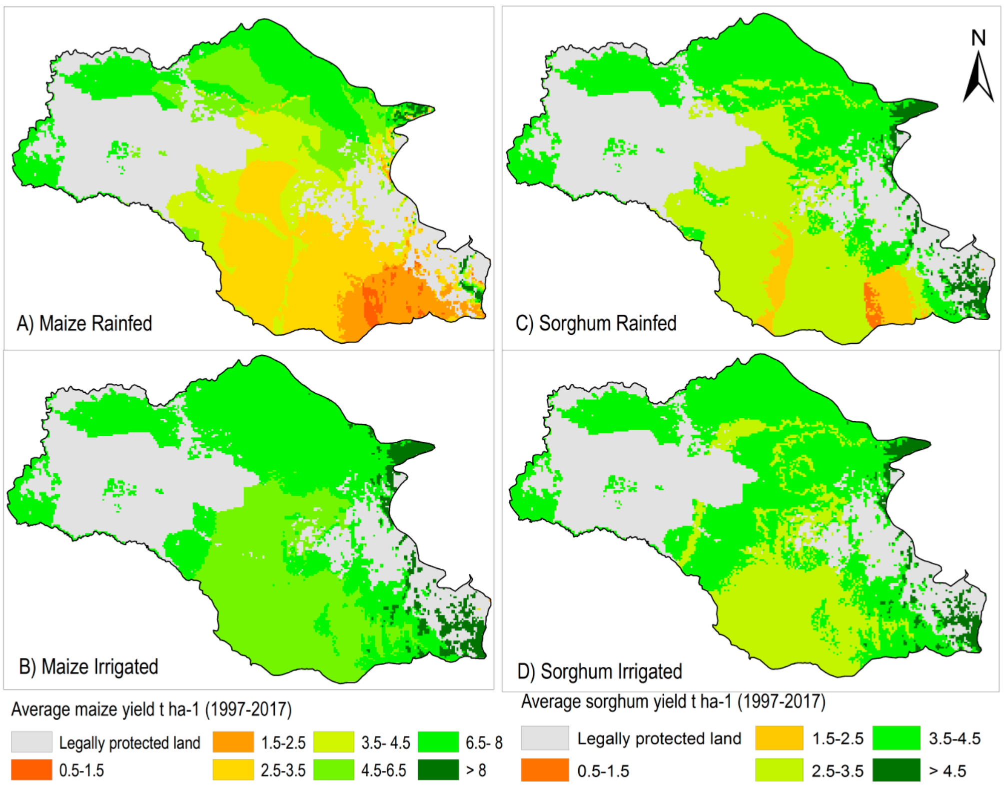

Figure 4. Average maize and sorghum yield on the total potential cropland area in high input-rainfed (HIR) and high input-irrigated (HII) scenarios. Potential yield which is simulated based on PROMET: HIR maize (**A**) & sorghum (**C**) on the potential cropland (including the current cropland) identified as low environmental opportunity cost and legally available lands where it is possible to convert the tract of land to cropland with rain-fed agriculture. HII maize (**B**) & sorghum (**D**) show simulated potential yields assuming perfect irrigation (no water stress).

3.2. Effect of Scenarios on the Potential Crop Production (1997–2017)

By identifying the 30% and 50% of all harvested pixels in Figure 4 which show the highest yields, we realize the spatial distribution of the two expansion assumptions TOP 30 and TOP 50. The resulting spatial expansion of cropland in Gambella is shown in Figure 5, together with the actual cropland. Figure 5 shows that expansion is predominantly identified in the north and west of Gambella. PROMET simulates the average potential yield of maize in rain-fed agriculture in the LIR 30 and HIR 30 scenarios to be 2.9 t ha^{-1} and 7.5 t ha^{-1}, respectively. In HII 30, irrigation increases the average maize yields from 7.5 to 7.7 t ha^{-1}. Average sorghum yield in the LIR 30 and HIR 30 scenarios is around 2.0 and 4.0 t ha^{-1}, respectively. At the same time in HII 30 irrigation increases the average yield of sorghum from 4.0 t ha^{-1} to 4.3 t ha^{-1}. Similarly, in LIR 50 and HIR 50, average maize yield in the region is 2.9 t ha^{-1} and 7.5 t ha^{-1} respectively, whereas in HII 50 average maize yield is around 7.7 t ha^{-1}. On the other hand, in LIR 50 and HIR 50, average sorghum yield is 2.1 t ha^{-1} and 4.1 t ha^{-1} respectively, while in HII 50 average sorghum yield is 4.3 t ha^{-1}. The result indicates that the average yield of maize and sorghum in HIR 30 and HIR 50, as also in HII 30 and HII 50, does not show any significant difference.

The result shows that average maize and sorghum reference yield production are 0.4 Mt and 0.3 Mt respectively from 1997–2017. In the LIR 30, maize average yield production is 1.8 Mt and it increases by 350% compared to the average maize yield reference production. In the HIR 30 and HII 30 average maize production is 4.4 Mt and 4.5 Mt respectively, increasing by 1000% and 1025% respectively compared to the average maize yield reference production. The small percentage increase in production from the HIR 30 to the HII 30 scenario confirms the excellent natural suitability and adequacy of rainfall of Gambella region for crop production. In the LIR 50, average maize production is 2.5 Mt and increases by 525% compared to the average maize yield reference production, while in the HIR 50 and HII 50 the average maize yield production is 6.1 Mt and 6.3 Mt, respectively. In the LIR 50 and HIR 50, average maize yield production is about 5 and 15 times respectively of the average maize reference yield production.

The result indicates that in the LIR 30 scenario the average sorghum yield production is 1.2 Mt and this is an increase of 300% compared to average sorghum reference yield production. In the HIR 30 and HII 30, average sorghum yield production is 2.4 Mt and 2.5 Mt respectively, increasing by 700% and 733% respectively compared to today's production/average sorghum reference yield production. Again, the effect of irrigation is marginal for sorghum. Under LIR 50 the average sorghum yield production is 1.7 Mt and increases by about 467% compared to average sorghum reference yield production. By repeating the same simulations, sorghum average yield production on the potential cropland in the HIR 50 and HII 50 is 3.4 Mt and 3.5 Mt respectively, reflecting an increase of 1033% and 1067% respectively compared to the average sorghum reference yield production. This yield production result shows that the total simulation potential production of HIR and HII in the region does not reflect any significant difference, which implies that annual rainfall of the region is enough for production of maize and sorghum. Figure 5 shows that spatial distribution of the total area coverage of the two scenarios (TOP 30 and TOP 50) would be located in the northern parts of the region where there is high yield production per ha. Both cropland expansion scenarios in the region could take place at the expense of tropical grasslands and sparsely vegetated lands of the region (see, e.g., Reference [39]).

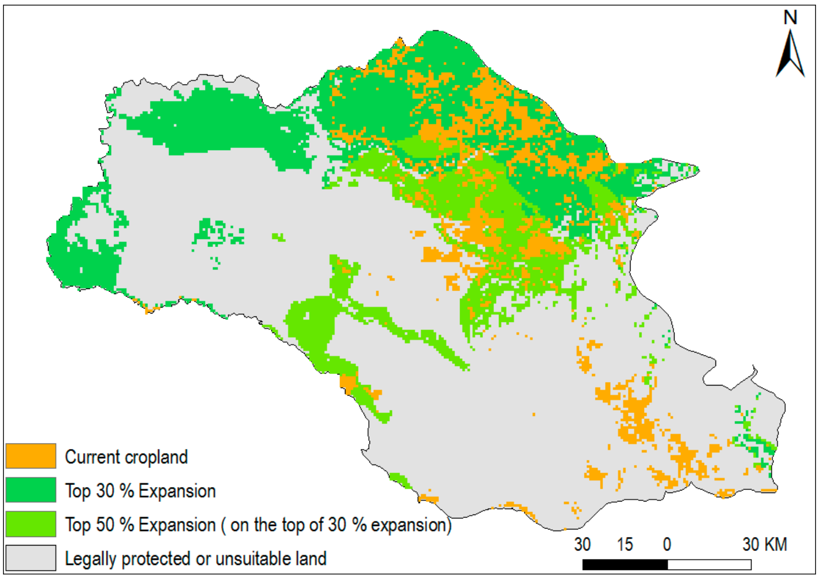

Figure 5. The total area coverage of current cropland, TOP 30 and TOP 50 land use scenarios and legally protected area in the Gambella Region.

3.3. Scenarios' Effect on the Potential Calorie Crop Production and Calorie Intake

Section 3.2 documented the huge gap between reference and simulated potential crop production in the region. In order to convert reference and potential production figures into meaningful information with respect to food security for the residents of Gambella, the values have to be converted from mass into caloric production. The result shows that total average reference crop calorie production is around 1.4×10^{12} kcal year^{-1} from 1997–2017. In LIR 30 the total average crop calorie production is around 5.40×10^{12} kcal year^{-1}, which is an increase of around 286% compared to average reference crop calorie production. Total average crop calorie production of HIR 30 is about 1.20×10^{13} kcal year^{-1}. The simulated potential average crop calorie production of HII 30 is very close to the HIR caloric production, at 1.23×10^{13} kcal year^{-1}, which is a potential increase of 778% compared to reference crop calorie production.

In LIR 50 the simulated average total crop calorie production is 7.4×10^{12} kcal year^{-1} and it shows an increase of 428% compared to the reference crop calorie production. Similarly, in HIR 50 the result shows that the average total crop calorie production is 1.67×10^{13} kcal year^{-1} (as illustrated in Table 1). This is an increase of 1092% compared to the reference calorie crop production. In irrigated agriculture, average HII 50 crop calorie production is simulated to be 1.70×10^{13} kcal year^{-1}, which shows only about a 1.8% increase over the simulated HIR 50 crop calorie production. In general, the difference between rain-fed and irrigated agricultural crop calorie production is insignificant.

The reference crop calorie production could feed around 1.7 million people, assuming a daily diet of 2200 kcal/cap/day. Table 1 shows that the simulated potential LIR 30 and HIR 30 could feed around 6.6 and 15.0 million people, respectively. The same calculations reveal that within the LIR 50 low-intensity/large expansion scenario, Gambella's agriculture could supply the necessary calories for 9.2 million people. Improving agricultural technology, infrastructure, education and governance for the HIR 50 scenario would further increase to 21.0 million the number of people that can be fed by Gambella's agriculture. However, the introduction of irrigation in the HIR scenario only marginally increases this number, to around 21.3 million people. This indicates that the simulated potential of HIR 50 and HII 50 potential crop calorie production can feed about 19 times as many people as the reference crop calorie production. The results of the scenario simulations also make clear that the total potential production of calories in all scenarios far exceeds the current and possible future caloric demand of Gambella's population, thereby also freeing food resources for the national and international markets.

Table 1. Crop (Mt year^{-1}) and calorie (kcal year^{-1}) production and number of people that can be nourished in the land use scenarios, with absolute number and relative percentage difference with reference to the reference yield/production.

TOP 30% Area Scenario		**LIR 30**	**HIR 30**	**HII 30**
Crop production	Maize	1.8 +350%	4.4 +1000%	4.5 +102%
	Sorghum	1.2 +300%	2.4 +700%	2.5 +733%
Crop Calorie production		5.4×10^{12} +286%	1.20×10^{13} +757%	1.23×10^{13} +778%
Number of people nourished (million)		6.6 +288%	15 +782%	15.5 +812%
TOP 50% Area Scenario		**LIR 50**	**HIR 50**	**HII 50**
Crop production	Maize	2.5 +525%	6.1 +1425%	6.3 +1475%
	Sorghum	1.7 +467%	3.4 +1033%	3.5 +1067%
Crop Calorie production		7.4×10^{12} +428%	1.67×10^{13} +1092%	1.70×10^{13} +1114%
Number of people nourished (million)		9.2 +441%	21.0 +1135%	21.3 +1153%

4. Discussion

In Gambella, agricultural intensification and cropland expansion are the two major policies/strategies to raise crop yields in particular and agricultural output in general [3]. Agricultural intensification by raising agricultural inputs to increase per-hectare yields has become central to policy formulation, primarily as a strategy for reducing agriculture encroachment into forests, protected areas and wetland areas. On the other hand, in Gambella cropland expansion is occurring due to rising food demand and population growth. According to UN reports, Ethiopia's population is expected to increase dramatically in the next 20–25 years [1,2], with the increase in food production falling behind population increase. Thus, we are arguing here that Gambella can serve as a backup for the country's potential food production.

Gambella region has huge potential for agricultural production (intensification) and an abundance of unutilized land (expansion) and has sufficient rainfall [38]. Our findings show that within Gambella's suitable cropland, the quantum of calories that can potentially be produced in HIR 50 agriculture can nourish 18% of today's total population of Ethiopia or 10% of the total population of Ethiopia in 2050. Thus, Gambella could potentially serve as a bread basket to enable food security for the country. Currently, the population of the region is around 436,000, which is about 0.5% of the total population of Ethiopia. Our results indicate that the population of the study area can be self-sufficient even with the very conservative assumptions underlying the LIR 30 scenario and that the production can even increase by better organizing and managing the region's farming practices. In recent decades, several agricultural development activities have been carried out in the region to achieve sustainable production. In the 1990s, there were no trained agricultural development workers. However, since the beginning of the current century a total of 1700 youths have been trained as agricultural extension workers. Currently, these agricultural extension workers are active in the region's agriculture offices, assisting and teaching how subsistence farmers can minimize the yield gaps [62]. The major objective of these agriculture extension workers is also to focus on training local farmers to be efficient in planting and harvesting and to adopt modern agricultural systems and technologies [62,63]. Yet, the average yield gap between the small-scale farmers' production and the simulated potential yield is quite large.

A lack of knowledge, poor agriculture technology and lack of modern inputs and innovations are the main contributory factors for low yield production per hectare in the region [38,64,65].

Our findings for potential yields are in agreement with other studies at country level or global scale. According to international food policy research institute (IFPRI) the potential production of average maize yield is around 4.7 t ha^{-1} on-farm field trials at country level, when cultivated with fertilizer, hybrid seed and farm management practices [66]. A local case study in Central Rift Valley region of Ethiopia shows similar results to our study. While we estimated an average water-limited potential yield for maize of 6.1 t ha^{-1}, the average maize water-limited potential yield was 6.0 t ha^{-1} for the 2015/2016 seasons [21]. For sorghum, Kinfe and Tesfaye [67] found an average potential yield of 3.9 t ha^{-1} in the moist lowlands of the country. The global GAEZ model approach at 5 arc minutes spatial resolution estimated the average maize and sorghum potentials to be 10.6 t ha^{-1} and 6 t ha^{-1} respectively for the Gambella region [68].

The study confirmed that irrigation does not contribute to higher potential yield levels in the Gambella region, because it turned out from the PROMET simulations that water was not the main constraint for maize and sorghum growth. It is also clear that the favourable natural conditions for agriculture in the region could help to produce adequate food to match the population growth of the area. Our findings show that the spatial distribution of yield production in the region is higher in the northern and central part of the region but declines towards the south-eastern part of the region, due to the prevailing Alisols that consist of 51% sand, 27% silt and 22% clay. The sandy soils lead to high percolation due to low field capacities, which finally results in water stress and low yields [1–3 t ha^{-1}]. In addition, this soil contains few nutrients and has high accumulation of clays in the subsoil [69,70]. With the exception of this particular area, however, crops in most parts of the region do not experience water stress.

For further studies, it is also important to consider climate change impacts on potential yields for future projections. For the Gambella region, climate projections assume a 2.57% and 2.35% increase of precipitation for RCP 8.5 and for RCP 2.6 respectively and an increase of temperature by 1.73 K for RCP 8.5 and by 0.75 K for RCP 2.6 until 2050 (model mean of all CMIP5 models [71]). The small increase in precipitation may not necessarily result in higher yields, since (1) the increase in precipitation is assumed to take place from September to December, which is beyond the current growing period of maize and sorghum (2) increased temperature might result in less water availability due to increased evaporation rates.

On the other hand, TOP 30 and TO P50 cropland expansion has been identified as improving the potential food production in the region by 2050. However, the TOP 30 and TOP 50 cropland expansion for agriculture could threaten the native ecosystems [72]. In both scenarios, sufficient agricultural production to meet the human demand for food while maintaining the ecosystem functions and minimizing the environmental impacts is the greatest challenge [73,74] in the region. While we do not consider utilizing any legally protected land for expansion, our study also does not consider distributions of endemic richness and biodiversity. Since we have assumed the areas best suited for expansion, further investigations are necessary to determine whether these identified best expansion areas are important for biodiversity or other ecosystem service functions and consequently should be protected and preserved.

In Gambella, tropical grassland cover was 1,370,000 ha in 1987 and it has declined to around 911,200 ha in 2017 due to cropland expansion. If the cropland expansion continues at the same rate as is happening today, then around 504,680 ha tropical grasslands are expected to be converted into cropland by 2050 [39]. Meeting this challenge requires better understanding of the environmental impact of TOP 30 and TOP 50 cropland expansion in the region. Thus, when making policies it is important to focus on the role of cropping intensity related to food production, land use management and planning. Our findings also demonstrate that currently intensification may provide a promising opportunity to increase Gambella region's food production without the need for cropland expansion. In the past, because of cropland expansion widespread land and resource conversion has been occurring in many parts of the region, mainly due to large-scale farm investment and resettlement (internal migration) from other regions [75,76].

To achieve the potential and sustainable food production in the future and to export significant food resources from the region to the national and international markets, the current status of agricultural production and estimated yields gaps, as well as the sustainability of the agricultural management and cropland expansion, need to be taken into account [77]. Based on this information, well-targeted land management decisions and potential food production can be achieved [48] in Gambella region.

5. Conclusions

This paper presents the Gambella region in Ethiopia as a case study for systematic exploration of the potential for agricultural intensification and cropland expansion to increase caloric production and food security. Realistic assumptions for intensification and cropland expansion were set and combined into 6 intensification/expansion scenarios which were analysed with respect to their food and caloric production potential. For this purpose, a spatially distributed hydro-ecological crop growth model identified the yield potentials of different management options as well as the feasible and most suitable regions for expansion of cropland. Overall, it can be stated that the framework that was set up to systematically develop and analyse the scenarios has proven its applicability for the selected test case. Since no assumptions which are specific to the test case enter the framework and since the selected model has already proven its global applicability, we assume that the framework is transferable to carry out similar studies in other regions of the globe.

The important practical results that can be drawn from the scenario analysis of the Gambella region are: (1) there is tremendous potential to increase rain-fed yields of maize and sorghum by increasing agricultural inputs through mechanization and fertilization and by improving infrastructure, education and governance; (2) there is similarly large potential for expanding cropland; the preferred areas for agricultural expansion in the region have been identified; (3) the rather low added potential of irrigation does not justify generally introducing it on a large scale; (4) Gambella's agricultural potential far exceeds its caloric demands and the region could theoretically go on without expansion, securing food supply for its current and future population and preserving natural resources like biodiversity, water resources and soil fertility for the demand of future generations; (5) the potential, if exploited, would allow export of significant food resources from Gambella to the national and international markets.

Supplementary Materials: The following are available online at http://www.mdpi.com/2077-0472/9/5/105/s1, Table S1: List of nutritive factors (f^i) for crop products.

Author Contributions: Conceptualization, A.W.D., F.Z. and W.M.; methodology, A.W.D., F.Z. and W.M.; software, W.M.; validation, A.W.D.; formal analysis, A.W.D., F.Z. and W.M.; investigation, A.W.D.; resources, A.W.D.; data curation, A.W.D.; writing—original draft preparation, A.W.D.; writing—review and editing, A.W.D., F.Z. and W.M.; visualization, A.W.D.; supervision, F.Z. and W.M. All authors read and approved the final manuscript.

Acknowledgments: Our special gratitude goes to the Ethiopian Ministry of Agriculture (MOA) staff, National Agricultural Statistic Service office, Ethiopia's annual Agricultural Sample Survey (AgSS) office and Ethiopia's Central Statistics Authority (CSA) for their support during the field data collection in 2018. At last but not least, I wish to acknowledge the financial support of German Academic Exchange Service (DAAD) and for giving me the opportunity to pursue my doctoral degree in Germany.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. World Population Review. Ethiopia Population. Available online: https://www.worldpopulationreview.com/countries/ethiopia-population/ (accessed on 13 January 2019).
2. Bekele, A.; Lakew, Y. *Projecting Ethiopian Demographics from 2012–2050 Using the Spectrum Suite of Models*; Ethiopian Public Health Association (EPHA): Addis Ababa, Ethiopia, 2014.
3. Mekuria, W. The link between agricultural production and population dynamics in Ethiopia: A review. *Adv. Plants Agric. Res.* **2018**, *8*, 348–353. [CrossRef]

4. IFAD. HIGHLIGHTS ANNUAL REPORT 2012. Available online: https://www.ifad.org/documents/38714170/39625681/annual+report+2012+english+final+print.pdf/664e5cf9-8166-4d43-9db2-f5d4b6a9eb03 (accessed on 3 November 2019).
5. Demeke, M.; Guta, F.; Ferede, T.; ADDIS ABABA. *Agricultural Development in Ethiopia: Are There Alternatives to Food Aid?* Department of Economics, Addis Ababa University: Addis Ababa, Ethiopia, 2004. Available online: www.sarpn.org.za/documents/d0001583/FAO2005_Casestudies_Ethiopia.pdf (accessed on 12 February 2019).
6. Ayenew, M.M.; Kopainsky, B. Food insecurity in Ethiopia: Population, food production and market. In Proceedings of the 32nd International Conference of the System Dynamics Society, Delft, The Netherlands, 20–24 July 2014.
7. Endalew, B.; Muche, M.; Tadesse, S. Assessment of food security situation in Ethiopia: A Review. *Asian J. Agric. Res.* **2015**, *9*, 55–68. [CrossRef]
8. Kugbei, S.; Turner, M.; Witthaut, P. *Finance and Management of Small-Scale Seed Enterprises*; ICARDA: Beirut, Lebanon, 2000.
9. Se, A.S.T.; Dorosh, P.; Gemessa, S.A. *Crop Production in Ethiopia: Regional Patterns and Trends*; International Food Policy Research Institute: Addis Ababa, Ethiopia, 2011; p. 53.
10. Schneider, K.; Anderson, L. Yield gap and productivity potential in Ethiopian agriculture: Staple grains & pulses. *EPAR Brief* **2010**, *98*. Available online: www.evans.uw.edu/policy-impact/epar/research/yield-gap-and-productivity-potential-ethiopian-agriculture-staple-gains (accessed on 15 November 2018).
11. Von Grebmer, K.; Bernstein, J.; de Waal, A.; Prasai, N.; Yin, S.; Yohannes, Y. *2015 Global Hunger Index: Armed Conflict and the Challenge of Hunger*; International Food Policy Research Institute: Washington, DC, USA, 2015.
12. Foley, J.A.; Ramankutty, N.; Brauman, K.A.; Cassidy, E.S.; Gerber, J.S.; Johnston, M.; Mueller, N.D.; O'Connell, C.; Ray, D.K.; West, P.C. Solutions for a cultivated planet. *Nature* **2011**, *478*, 337. [CrossRef]
13. Phalan, B.; Green, R.; Balmford, A. Closing yield gaps: Perils and possibilities for biodiversity conservation. *Phil. Trans. R. Soc. B* **2014**, *369*, 20120285. [CrossRef]
14. Byerlee, D.; Stevenson, J.; Villoria, N. Does intensification slow crop land expansion or encourage deforestation? *Glob. Food Secur.* **2014**, *3*, 92–98. [CrossRef]
15. Barbier, E.B. Explaining agricultural land expansion and deforestation in developing countries. *Am. J. Agric. Econ.* **2004**, *86*, 1347–1353. [CrossRef]
16. Tilman, D.; Balzer, C.; Hill, J.; Befort, B.L. Global food demand and the sustainable intensification of agriculture. *Proc. Natl. Acad. Sci. USA* **2011**, *108*, 20260–20264. [CrossRef] [PubMed]
17. Chamberlin, J.; Jayne, T.; Headey, D. Scarcity amidst abundance? Reassessing the potential for cropland expansion in Africa. *Food Policy* **2014**, *48*, 51–65. [CrossRef]
18. Tadesse, D. *Gambella The Impact of Local Conflict on Regional Security*; Institute for Security Studies: Addis Ababa, Ethiopia, 2007.
19. Cascão, A.E. *Resource-Based Conflict in South Sudan and Gambella (Ethiopia): When Water, Land and Oil Mix with Politics*; ISCTE: Lisbon, Portugal, 2013.
20. Hillocks, R. Addressing the yield gap in Sub-Saharan Africa. *Outlook Agric.* **2014**, *43*, 85–90. [CrossRef]
21. Admassie, A.; Assefa, B.; Descheemaeker, K. *Reducing the Maize Yield Gap in Ethiopia: Analysis and Policy Simulation*; Ethiopian Economics Association: Addis Ababa, Ethiopia, 2017.
22. Alemu, G.T.; Berhanie Ayele, Z.; Abelieneh Berhanu, A. Effects of Land Fragmentation on Productivity in Northwestern Ethiopia. *Adv. Agric.* **2017**, *2017*, 1–9. [CrossRef]
23. Sewnet, Y.; Elemo, E.; Derso, D. A review of agricultural research, extension and farmers linkage in Ethiopia. *Agric. Biol. J. Am.* **2016**, *7*, 116–120.
24. Gálvez-Nogales, E.; Fonseca, J. *Institutional Procurement of Staples from Smallholders: The Case of Purchase for Progress in Ethiopia*; FAO: Rome, Italy, 2014.
25. Lobell, D.B.; Cassman, K.G.; Field, C.B. Crop yield gaps: Their importance, magnitudes, and causes. *Annu. Rev. Environ. Resour.* **2009**, *34*, 179–204. [CrossRef]
26. Mueller, N.D.; Gerber, J.S.; Johnston, M.; Ray, D.K.; Ramankutty, N.; Foley, J.A. Closing yield gaps through nutrient and water management. *Nature* **2012**, *490*, 254–257. [CrossRef] [PubMed]
27. Mauser, W.; Klepper, G.; Zabel, F.; Delzeit, R.; Hank, T.; Putzenlechner, B.; Calzadilla, A. Global biomass production potentials exceed expected future demand without the need for cropland expansion. *Nat. Commun.* **2015**, *6*, 8946. [CrossRef] [PubMed]

28. Müller, C.; Elliott, J.; Chryssanthacopoulos, J.; Arneth, A.; Balkovic, J.; Ciais, P.; Deryng, D.; Folberth, C.; Glotter, M.; Hoek, S. Global gridded crop model evaluation: Benchmarking, skills, deficiencies and implications. *Geosci. Model Dev. Discuss.* **2017**, *10*, 1403–1422. [CrossRef]
29. Woube, M. Flooding and sustainable land–water management in the lower Baro–Akobo river basin, Ethiopia. *Appl. Geogr.* **1999**, *19*, 235–251. [CrossRef]
30. Gebresenbet, F. Land acquisitions, the politics of dispossession, and state-remaking in Gambella, Western Ethiopia. *Afr. Spectr.* **2016**, *51*, 5–28. [CrossRef]
31. Wakuma Abaya, S.; Mandere, N.; Ewald, G. Floods and health in Gambella region, Ethiopia: A qualitative assessment of the strengths and weaknesses of coping mechanisms. *Glob. Health Action* **2009**, *2*, 2019. [CrossRef]
32. Dika, G. Impacts of Climate Variability and Households Adaptation Strategies in Lare District of Gambella Region, South Western Ethiopia. *J. Earth Sci. Clim. Chang.* **2018**, *9*, 2. [CrossRef]
33. Sewonet, A. *Breaking the Cycle of Conflict in Gambella Region*; UN-Emergencies Unit for Ethiopia: Addis Ababa, Ethiopia, 2002.
34. Awulachew, S.B.; Yilma, A.D.; Loulseged, M.; Loiskandl, W.; Ayana, M.; Alamirew, T. *Water Resources and Irrigation Development in Ethiopia*; IWMI: Colombo, Sri Lanka, 2007; ISBN 978-92-9090-680-3.
35. Central Statistical Agency. *Population Projection of Ethiopia for All Regions At Wereda Level from 2014–2017*; Central Statistical Agency: Addis Ababa, Ethiopia, 2018.
36. Olay, K.O.; Okumo, O.O. The Effect of Large Agricultural Investment Projects on the Local People in Ethiopia "The Case of Gambella Region". *Imp. J. Interdiscip. Res.* **2017**, *3*, 732–740.
37. Degife, A.W.; Mauser, W. Socio-economic and Environmental Impacts of Large-Scale Agricultural Investment in Gambella Region, Ethiopia. *J. US-China Public Adm.* **2017**, *14*, 183–197.
38. Yassin, A. *Transnational Large Scale Agricultural Firms in Gambella Regional State, Ethiopia: Local Potentials, Opportunities and Constraints for Market Linkage and Contractual Farming Schemes*; Future Agricultures Consortium: Brighton, UK, 2014.
39. Degife, A.W.; Zabel, F.; Mauser, W. Assessing land use and land cover changes and agricultural farmland expansions in Gambella Region, Ethiopia, using Landsat 5 and Sentinel 2a multispectral data. *Heliyon* **2018**, *4*, e00919. [CrossRef]
40. Snow, K.H. *Livelihoods & Vulnerabilities Study Gambella Region of Ethiopia*; UNICEF: Addis Ababa, Ethiopia, 2006; p. 13.
41. Lemessa, D.; Officer, U.-E.A.F. *Food Shortages and Seasonal Floods: Major Recurrent Threats to Gambella Region*; Undp Emergencies Unit Ethiopia: Addis Ababa, Ethiopia, 1999.
42. Dorosh, P.; Rashid, S. *Food and Agriculture in Ethiopia: Progress and Policy Challenges*; University of Pennsylvania Press: Philadelphia, PA, USA, 2013.
43. Mann, M.; Warner, J. *Ethiopian Wheat Yield and Yield Gap Estimation: A Small Area Integrated Data Approach*; International Food Policy Research Institute: Washington, DC, USA, 2015.
44. Woo, J. *Rainfall Variability and Crop Yield Potential*; International Food Policy Research Institute: Washington, DC, USA, 2010.
45. Mauser, W.; Bach, H.; Frank, T.; Hank, T.; Koch, F.; Marke, T.; Muerth, M.; Prasch, M.; Strasser, U.; Zabel, F. PROMET–Processes of Mass and Energy Transfer. An Integrated Land Surface Processes and Human Impacts Simulator for the Quantitative Exploration of Human-Environment Relations. Available online: http://www.geographie.unimuenchen.de/department/fiona/forschung/projekte/promet_handbook/index.html (accessed on 16 November 2018).
46. Zabel, F.; Mauser, W. 2-way coupling the hydrological land surface model PROMET with the regional climate model MM5. *Hydrol. Earth Syst. Sci.* **2013**, *17*, 1705–1714. [CrossRef]
47. Hank, T.B.; Bach, H.; Mauser, W. Using a remote sensing-supported hydro-agroecological model for field-scale simulation of heterogeneous crop growth and yield: Application for wheat in central Europe. *Remote Sens.* **2015**, *7*, 3934–3965. [CrossRef]
48. Bach, H.; Klug, P.; Ruf, T.; Migdall, S.; Schlenz, F.; Hank, T.; Mauser, W. Satellite image simulations for model-supervised, dynamic retrieval of crop type and land use intensity. In Proceedings of the 36th International Symposium on Remote Sensing of Environment, Berlin, Germany, 11–15 May 2015; pp. 1–7.
49. Fantaye, K.T. *Application of the GYGA Approach to Ethiopia*; Global Yield Gap Atlas: Addis Ababa, Ethiopia, 2016.

50. Van Ittersum, M.K.; Cassman, K.G.; Grassini, P.; Wolf, J.; Tittonell, P.; Hochman, Z. Yield gap analysis with local to global relevance—A review. *Field Crop. Res.* **2013**, *143*, 4–17. [CrossRef]
51. Dee, D.P.; Uppala, S.M.; Simmons, A.; Berrisford, P.; Poli, P.; Kobayashi, S.; Andrae, U.; Balmaseda, M.; Balsamo, G.; Bauer, D.P. The ERA-Interim reanalysis: Configuration and performance of the data assimilation system. *Q. J. R. Meteorol. Soc.* **2011**, *137*, 553–597. [CrossRef]
52. Dudley, N.; Stolton, S. Defining protected areas: An international conference in Almeria, Spain. *Iucngland* **2008**, 21–26.
53. EPRDF. A proclamation to provide for the conservation. Development and utilization of forests. In *Negarit Gazeta*; Proclamation NO. 94/1994; Ministry of Natural Resources Development and Environmental Protection, Ed.; Berhanena Selam Printing: Addis Ababa, Ethiopia, 1994.
54. Amsalu, T.; Addisu, S. A review of Wetland Conservation and Management Policy in Ethiopian. *Int. J. Sci. Res. Publ.* **2014**, *4*, 656–662.
55. Ray, D.K.; Mueller, N.D.; West, P.C.; Foley, J.A. Yield trends are insufficient to double global crop production by 2050. *PLoS ONE* **2013**, *8*, e66428. [CrossRef]
56. Central Statistical Agency. *Agricultural Sample Survey Area and Production of Major Crops*; Ministry of Agriculture Ethiopia: Addis Ababa, Ethiopia, 2017.
57. Central Statistical Agency. *Agricultural Sample Survey Area and Production of Major Crops (Private Peasant Holdings, Meher Season)*; Central Statistical Agency (CSA): Addis Ababa, Ethiopia, 2017; pp. 1–112.
58. FAO. *A Handbook Food Balance Sheets*; FAO: Rome, Italy, 2001.
59. Pradhan, P.; Lüdeke, M.K.; Reusser, D.E.; Kropp, J.P. Embodied crop calories in animal products. *Environ. Res. Lett.* **2013**, *8*, 044044. [CrossRef]
60. Davis, K.F.; Seveso, A.; Rulli, M.C.; D'Odorico, P. Water savings of crop redistribution in the United States. *Water* **2017**, *9*, 83. [CrossRef]
61. United Nations Department of Economic and Social Affairs. *World Population Prospects, United Nations Department of Economic and Social Affairs*; Population Division: New York, NY, USA, 2017.
62. Abdusemed, A. Ethiopia: Gambella Is Thriving in Agricultural Productivity. *The Ethiopian Herald*, 30 December 2015.
63. Dula, T. Review on the Contribution of Agricultural Extension on Increasing Smallholder Farm Productivity in Case of Ethiopia. *J. Cult. Soc. Dev.* **2018**, *40*, 42–49.
64. Kagima, D.K. *Training Programs in Sustainable Agriculture for Postharvest Loss Minimization and Storage: A Case Sudy in Ethiopia*; Iowa State University: Ames, IA, USA, 2005.
65. Abate, T.; Shiferaw, B.; Menkir, A.; Wegary, D.; Kebede, Y.; Tesfaye, K.; Kassie, M.; Bogale, G.; Tadesse, B.; Keno, T. Factors that transformed maize productivity in Ethiopia. *Food Secur.* **2015**, *7*, 965–981. [CrossRef]
66. Rashid, S.; Getnet, K.; Lemma, S. Maize value chain potential in Ethiopia: Constraints and opportunities for enhancing the system. *F1000Research* **2019**, *3*, 2–40.
67. Kinfe, H.; Tesfaye, A. Yield performance and adoption of released Sorghum varieties in Ethiopia. *Edelweiss Appl. Sci. Technol.* **2018**, *2*, 46–55. [CrossRef]
68. Fischer, G.; Nachtergaele, F.O.; Prieler, S.; Teixeira, E.; Tóth, G.; van Velthuizen, H.; Verelst, L.; Wiberg, D. *Global Agro-Ecological Zones (GAEZ v3. 0)-Model Documentation*; IIASA: Laxenburg, Austria; FAO: Rome, Italy, 2012.
69. Batjes, N.H. Harmonized soil profile data for applications at global and continental scales: Updates to the WISE database. *Soil Use Manag.* **2009**, *25*, 124–127. [CrossRef]
70. Lakew, A.M.; Moog, O. *Top-down Operative Stream Classification System (typology) for Ethiopian Highlands*; Austrian Partnership Programme in Higher Education & Research for Development: Larima, Vienna, Austria, 2016; p. 23.
71. Taylor, K.E.; Stouffer, R.J.; Meehl, G.A. An Overview of CMIP5 and the Experiment Design. *Bull. Am. Meteorol. Soc.* **2012**, *93*, 485–498. [CrossRef]
72. Perrings, C.; Halkos, G. Agriculture and the threat to biodiversity in sub-saharan Africa. *Environ. Res. Lett.* **2015**, *10*, 095015. [CrossRef]
73. Godfray, H.C.J.; Garnett, T. Food security and sustainable intensification. *Philos. Trans. R. Soc. B Biol. Sci.* **2014**, *369*, 20120273. [CrossRef]

74. Molotoks, A.; Stehfest, E.; Doelman, J.; Albanito, F.; Fitton, N.; Dawson, T.P.; Smith, P. Global projections of future cropland expansion to 2050 and direct impacts on biodiversity and carbon storage. *Glob. Chang. Biol.* **2018**, *24*, 5895–5908. [CrossRef]
75. Teshome, M. Population growth and cultivated land in Rural Ethiopia: Land use dynamics, access, farm size, and fragmentation. *Resour. Environ.* **2014**, *4*, 148–161.
76. Devereux, S.; Sussex, I. *Food Insecurity in Ethiopia*; Institute for Development Studies: Brighton, UK, 2000.
77. Jones, J.W.; Antle, J.M.; Basso, B.; Boote, K.J.; Conant, R.T.; Foster, I.; Godfray, H.C.J.; Herrero, M.; Howitt, R.E.; Janssen, S. Toward a new generation of agricultural system data, models, and knowledge products: State of agricultural systems science. *Agric. Syst.* **2017**, *155*, 269–288. [CrossRef]

Publication III

Degife, A. W., F. Zabel and W. Mauser (2019). “Climate change impacts on potential maize yields in Gambella Region, Ethiopia." Regional Environmental Change REEC-D-19-00600. **Under review**

Climate change impacts.pdf

.

Regional Environmental Change

Climate change impacts on potential maize yields in Gambella region, Ethiopia

--Manuscript Draft--

Manuscript Number:	REEC-D-19-00600
Full Title:	Climate change impacts on potential maize yields in Gambella region, Ethiopia
Article Type:	Original Research Article
Keywords:	Climate change; Agriculture; Regional Study; Crop Model
Corresponding Author:	Azeb Degife, M.A and MSc. Ludwig-Maximilians-Universitat Munchen München, GERMANY
Corresponding Author Secondary Information:	
Corresponding Author's Institution:	Ludwig-Maximilians-Universitat Munchen
Corresponding Author's Secondary Institution:	
First Author:	Azeb Degife, M.A and MSc.
First Author Secondary Information:	
Order of Authors:	Azeb Degife, M.A and MSc.
	Florian Zabel, Dr
	Wolfram Mauser, Prof. Dr
Order of Authors Secondary Information:	
Funding Information:	
Abstract:	Changing climate conditions are supposed to have several impacts on agriculture. It is necessary understanding the different impacts of climate change on crop yields at regional scales for planning proper strategies. In this study, we systematically investigate climate change impacts on yields for the Gambella region in Ethiopia, exemplarily for maize. Here we show how yields change until 2100 for RCPs 2.6, 4.5, and 8.5 from a climate model ensemble under rainfed and irrigated conditions. While rainfed yields decrease by 15% and 14% respectively for RCPs 2.6 and 4.5, yields decrease by up to 32% under RCP 8.5. Except for RCP 8.5, yields are not further decreasing after 2040-2069. We found that temperature increase, changing soil water availability and atmospheric CO_2 concentration have different effects on the simulated yield potential. Our results demonstrate the dominance of heat response under future climate conditions in the tropical Gambella region, contributing to 85% of total yields changes. Accordingly, irrigation will lose effectiveness for increasing yield when temperature becomes the limiting factor. CO_2 on the other hand, contributes positively to yield changes by 8.9% for RCP 8.5. For all scenarios, the growing period is shorted due to increasing temperature by up to 29 days for RCP 8.5. Our results suggest that new varieties with higher growing degree days are primarily required to the region for adapting to future climate conditions.
Additional Information:	
Question	**Response**
Has your submission been invited to a special issue currently in preparation for this journal?	No
If yes, please ensure that your submission occurs according to the approved plans of the respective guest editors. If this is the	

Climate change impacts on potential maize yields in Gambella region, Ethiopia

Azeb W. Degife*, Florian Zabel and Wolfram Mauser

Department of Geography, Ludwig-Maximilians-Universität München, Luisenstrasse 37, 80333 Munich, Germany

f.zabel@lmu.de (F.Z.); w.mauser@lmu.de (W.M.)
* Correspondence: a.degife@iggf.geo.uni-muenchen.de; Tel.: +49-89-2180-6695

Length of the manuscript

The length of the manuscript must be indicated, consisting of

- **5240** The number of words, counting from the top of the title page, including abstract, keywords and acknowledgements to the end of text (before the reference list)
- **7** Figs and **1** tables = 2400 words
- **7640** The number of words, including the count for the Fig.s and tables

Abstract

Changing climate conditions are supposed to have several impacts on agriculture. It is necessary understanding the different impacts of climate change on crop yields at regional scales for planning proper strategies. In this study, we systematically investigate climate change impacts on yields for the Gambella region in Ethiopia, exemplarily for maize. Here we show how yields change until 2100 for RCPs 2.6, 4.5, and 8.5 from a climate model ensemble under rainfed and irrigated conditions. While rainfed yields decrease by 15% and 14% respectively for RCPs 2.6 and 4.5, yields decrease by up to 32% under RCP 8.5. Except for RCP 8.5, yields are not further decreasing after 2040-2069. We found that temperature increase, changing soil water availability and atmospheric CO_2 concentration have different effects on the simulated yield potential. Our results demonstrate the dominance of heat response under future climate conditions in the tropical Gambella region, contributing to 85% of total yields changes. Accordingly, irrigation will lose effectiveness for increasing yield when temperature becomes the limiting factor. CO_2 on the other hand, contributes positively to yield changes by 8.9% for RCP 8.5. For all scenarios, the growing period is shorted due to increasing temperature by up to 29 days for RCP 8.5. Our results suggest that new varieties with higher growing degree days are primarily required to the region for adapting to future climate conditions.

Keywords: Climate Change, Agriculture, Regional Study, Crop Model

1. Introduction

Many studies agree that climate change is real and that the poorest and most vulnerable people will be the most affected by reduced availability, lower quality and higher prices of food (Barbier and Hochard 2018; Diffenbaugh and Burke 2019; Hallegatte et al. 2018). The last three decades were each warmer than every previous decade since temperature records began in 1850 (IPCC 2014). However, there are significant regional differences in temperature and precipitation changes (IPCC 2013). Many studies have considered the impacts of future climate changes on food production at the global or very large scale (Iizumi et al. 2017; Lobell et al. 2008; Najafi et al. 2018; Parry et al. 2004).

However, there is a gap in regional impact studies, especially for Ethiopia, which is vulnerable to climate change, since it is not a food secure country (Alemu and Mengistu 2019; Cochrane 2018; Endalew et al. 2015; Mekonnen and Gerber 2017). Earlier studies on climate change impacts on crop production in Ethiopia were either at the national (Bryan et al. 2009; Kassie et al. 2014; Wubie 2015; Zerga and Gebeyehu 2016) or larger scale such as the East African regional levels (Abera et al. 2018; Leal Filho et al. 2017; Niang et al. 2014). There are only a few studies at subnational levels within Ethiopia (Abera et al. 2018).

Ethiopia's economy is highly dominated by agriculture (Alemu and Mengistu 2019; Alemu et al. 2003; Zerga and Gebeyehu 2016), contributing about 40 % of the GDP (Shiferaw 2017). The World Bank's analysis predicts that climate change will lower Ethiopia's gross domestic product (GDP) growth by 0.5 –2.5 % per annum (Tesfaye et al. 2016). In Ethiopia, effects of an enduring drought for continuous years from 1983-1985 reduced agricultural production in the county (Aragie 2013; Kassie et al. 2014). Food supply is one of society's key sensitivities to climate in Ethiopia (Porter et al. 2014).

The IPCC's fifth assessment report indicates that future climate change will lead to an increase in climate variability and in frequency and intensity of extreme events in Ethiopia (Niang et al. 2014). Over the past four decades changing precipitation patterns (both dry and wet periods) have been observed in many parts of Ethiopia (Aragie 2013; Seleshi and Zanke 2004). Thereby, precipitation has shown a general decreasing trend since the 1990s (Leal Filho et al. 2017). This decrease already manifests in multiple effects on agricultural production in Ethiopia (Aragie 2013; Seleshi and Zanke 2004). In the last three decades the Gambella region in the western part of Ethiopia was faced with frequent climatic variability and agro-ecological change (Dika 2018). The changing rainfall pattern in combination with warming trends could make rainfed agriculture more risky and barrier food production in Ethiopia (Tesfaye et al. 2016) and in the region. For future conditions, a temperature increase of 2 to 2.5°C is supposed to have significant implications on agriculture in parts of Africa (Belloumi 2014) and Ethiopian (Leal Filho et al. 2017). In general, climate change induced increases in temperatures, rainfall variation and the frequency and intensity of extreme weather events are adding pressures on Ethiopian agricultural production (Adhikari et al. 2015; Gbegbelegbe et al. 2014; Tesfaye et al. 2016). This creates challenges for the agricultural sector for possible future adaptation (FAO 2017).

For proper planning, it is required to investigate impacts of climate change on crop yields at regional scales. This is the first regional study that systematically investigates climate change impacts on agricultural production for Gambella in Ethiopia, exemplarily for maize. In 2016/2017 maize crop accounts for 57% of Gambella region's crop production by small scale farmers and 56% of the region's harvested area (Degife et al. 2019). The following study comprises a representative selection of climate change impact scenarios to show the range of possible futures for different representative concentration pathways (RCPs). The approach is based on climate model results, which feed a process based biophysical crop model that simulates crop yields under specific climate conditions.

2. Data and Methods

2.1 Study area

Gambella is one of nine administrative regions in the south-western part of Ethiopia. The region covers a total area of 25,521 km^2 (Tadesse 2007). It shares borders with South Sudan and two other Ethiopian regions: Oromia to the north and east and the Southern Nations, Nationalities and Peoples' Regional State (SNNPRS) to the South (Fig. S1). Gambella region altitude progressively declines from east to west, ranging from 2200–1000 m a.s.l. in the east, to 500–900 m in the center and 300–500 m in the west (Woube 1999). The region is highly suitable for agriculture (Zabel et al. 2014).

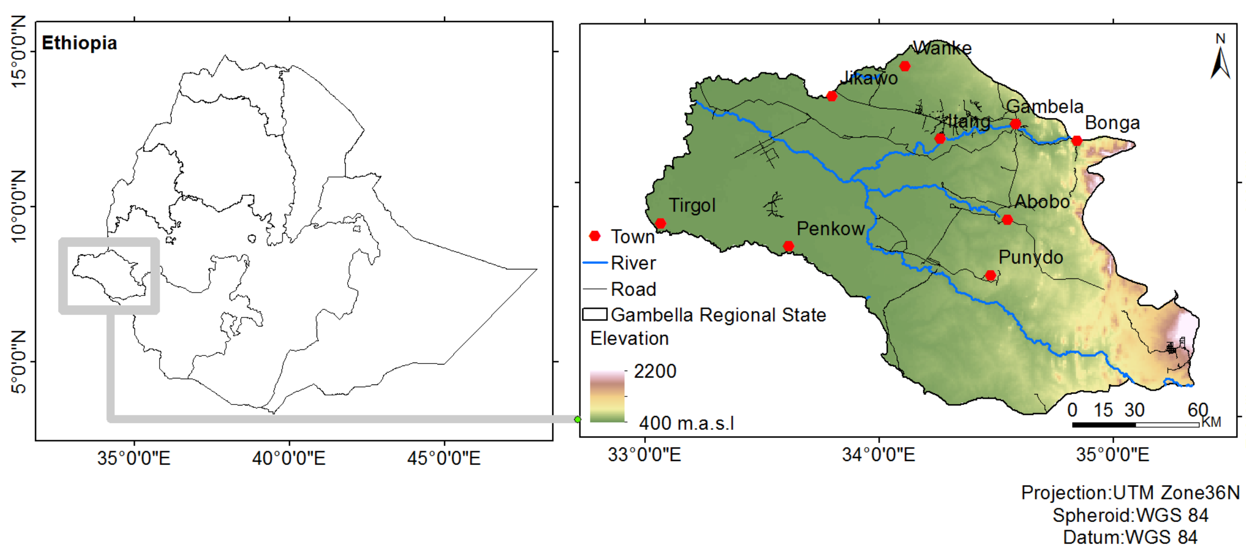

Fig. 1 Gambella locational map: Federal Democratic Republic of Ethiopia (left) and Gambella regional state (right)

2.2 Climate data

Dynamically downscaled general circulation models (GCM) projections have proven to be suitable tools for providing high-resolution climate drivers for regional and local assessments of climate change impacts and extremes (Shiferaw et al. 2018). We used climate data (near-surface air temperature, precipitation, surface downwelling longwave radiation, surface downwelling shortwave radiation, total cloud fraction, near-surface wind speed, sea level pressure, near-surface relative humidity) from the regional climate model Rossby Centre Regional Atmospheric Climate Model (RCA4) with large-scale forcing from five different GCMs (Table 1). The originated from the coupled model intercomparison project phase 5 (CMIP5). In order to capture the range of existing impact scenarios, we used three representative concentration pathways RCP 2.6, RCP 4.5 and RCP 8.5 (IPCC 2014; Van Vuuren et al. 2011).

RCA4 data was acquired over the African domain from the coordinated regional climate downscaling experiment (CORDEX) (Dosio and Panitz 2016) with horizontal grid spacing of 0.44° (≈50 km) and 3-hourly temporal resolution. The applied data includes the historical period (1970-2005) and the RCPs representing climate change scenarios from 2020 until 2099. Both, for the past and the future each RCA4 run representing an RCP consists of a five-member ensemble from five different driving GCMs.

Table 1: CMIP5 GCMs used in this study

Model	Description	Modeling Center
EC-EARTH	A European community Earth-System Model	EC-Earth consortium
HadGEM2-ES	Hadley Global Environmental Earth System Model 2	Met Office Hadley Centre(MOHC)
MIROC5	Model for Interdisciplinary Research on Climate	International Centre for Earth Simulation
MPI-M-MPI-ESM-LR	MPI Earth System Model running on low resolution grid	Max Planck Institute for Meteorology (MPI-M)
NCC-NorESM1-M	The Norwegian Earth System Model	Norwegian Climate Centre (NCC)

To use the climate data in the PROMET model (see 2.3), we applied a statistical downscaling to 30 arc seconds and a temporal interpolation to 1 hour. Additionally, a bias correction was applied to temperature and precipitation after the downscaling and temporal interpolation (Marke et al. 2014). For this we used global monthly observation climatology from the WorldClim database v2 at 30 arc seconds resolution (Fick and Hijmans 2017). It is representative for the time period 1970–2000. The bias correction ensures that the average 1970–2000 monthly bias corrected and interpolated set of 5 climate model results of air temperature and precipitation at each of the 30 arcsecond grid cells that encompass Gambella region closely resemble the monthly values in the Worldclim data set.

2.3 PROMET model

The PROMET model was applied to simulate crop growth of maize in the Gambella region (Delzeit et al. 2017; Hank et al. 2015; Mauser et al. 2015; Minoli et al. 2019; Zabel et al. 2019). It uses first order physical and physiological principles to determine net primary production and respiration based on approaches from (Ball et al. 1987; Farquhar et al. 1980; Xinyou and Van Laar 2005) combined with a phenology and a two-layer canopy architecture component. PROMET takes into account the dependency of net primary production and phenology on environmental conditions including meteorology, CO_2 concentration for C3 and C4 pathways as well as water and temperature stress. The mass and energy balance of the canopy and underlying soil surface are iteratively closed for each simulation time step. The canopy and phenology component allocates assimilates into the different plant organs of the canopy depending on the phenological stage of development. Assimilates that are accumulated within the fruit fraction during the growing period determine the dry biomass available for yield formation. The simulation is performed on an hourly time step to account for non-linear reactions of crop growth to abiotic conditions like water and temperature stresses. Depending on the reaction of the considered crop to meteorological and soil-specific conditions, the crop may either die due to water, heat or cold stress before being harvested or it may not reach maturity. In both cases, this results in total yield loss.

In the context of this study, we simulate maize potential yield, assuming a perfect crop management. This means that crop is sowed at the appropriate date, perfectly supplied with nutrients at any time and pests and diseases are assumed to be controlled. We simulated both, rainfed and irrigated practices, in order to quantify the effect of irrigation for possible future adaptation. In case of irrigation, we assume that no water stress occurs at any time.

Sowing dates are taken from available regional statistics for Gambella, stating that growing period starts in the middle of April. Sowing dates are kept constant and not shifted in this study in order to investigate the climate effect only. Maturity is simulated internally by PROMET according to the crop phenological progress.

We applied a settling time of 5 years (1970-1974) to all PROMET simulations for initializing soil moisture and other hydrological parameters, so that we use the 30a baseline period from 1975 to 2004.

2.4 Decomposition analysis

In order to separately quantify the different effects of increasing temperature, available soil water and atmospheric CO_2 concentration on the simulated potential yield, we applied a decomposition analysis for the 2070-2099 period. Therefore, we conducted all simulations for both, rainfed and irrigated conditions. Additionally, we conducted a control run with fixed CO_2 concentration at 360 ppm until 2099 to isolate the beneficial effects of CO_2.

First, to obtain the proportion of yield change due to temperature increase, we subtract 1975-2004 yields from yields in 2070-2099 from the irrigated fixed CO_2 run, where CO_2 and water have no effect. Second, we subtract the irrigated fixed CO_2 2070-2099 yields from the irrigated 2070-2099 yields with increased CO_2 concentration to obtain the isolated benefit from CO_2 fertilization. Third, we subtract the irrigated 2070-2099 yields from the rainfed yields to get the isolated effect of water stress on yields.

By comparing historical and future yields for the fixed irrigated CO_2 yields, besides temperature, also other effects are cumulated, such as changes of wind speed and radiation, that impact on yields. Since PROMET considers the available soil water for the simulation of crop water stress, including a detailed description of relevant hydrologic processes in the soil-plant-atmosphere continuum, we refer to the water stress effect rather than precipitation in our analysis.

2.5 Land-use scenario

In this study, we assume that agricultural land in Gambella will expand into the not-yet-used legally available land for agricultural expansion. Therefore, all our results refer to all current cropland area in addition to the Top50 expansion (Zabel et al. 2019) scenario according to (Degife et al. 2019). The scenario assumes the use of today's cropland in addition to the best (in terms of highest potential yields) 50% expansion area. The used land is assumed to be constant over time in order to not affect the results.

3. Results

In average for 2070-2099, temperature increases by 1.6 K, 2.6 K and 5.3 K under RCP 2.6, RCP 4.5 and RCP 8.5 scenarios for the Gambella region from April to September (Fig. 2), referring to the growing period of maize (Central Statistical Agency 2017). The model median of the average temperature in the region for the historical 1975-2004 period is 26.5°C.

Precipitation changes on average for 2070-2099 by -11.9%, -10.9% and -22.6% under RCP 2.6, RCP 4.5 and RCP 8.5 scenarios for the Gambella region over the fixed statistical growing period of maize (Fig. 2). The model median of the absolute amount of precipitation in the region for the historical 1975-2004 period is 611 mm. While the models agree quite well for temperature and precipitation change as can be seen by the model spread in Fig. 2, absolute precipitation values vary largely over historical periods (e.g. mean 1975-2004 values range between 888 mm for EC-EARTH and 530 mm for HadGEM2-ES). Overall, the tropical climate is characterized by hot temperatures and high precipitation.

The changing climate conditions have several impacts on maize yield that are described in the following, first showing impacts on rainfed maize, followed by showing impacts on irrigated maize. Subsequently, a decomposition analysis shows the different impacts of each, temperature, water availability and CO_2 on maize yield separately.

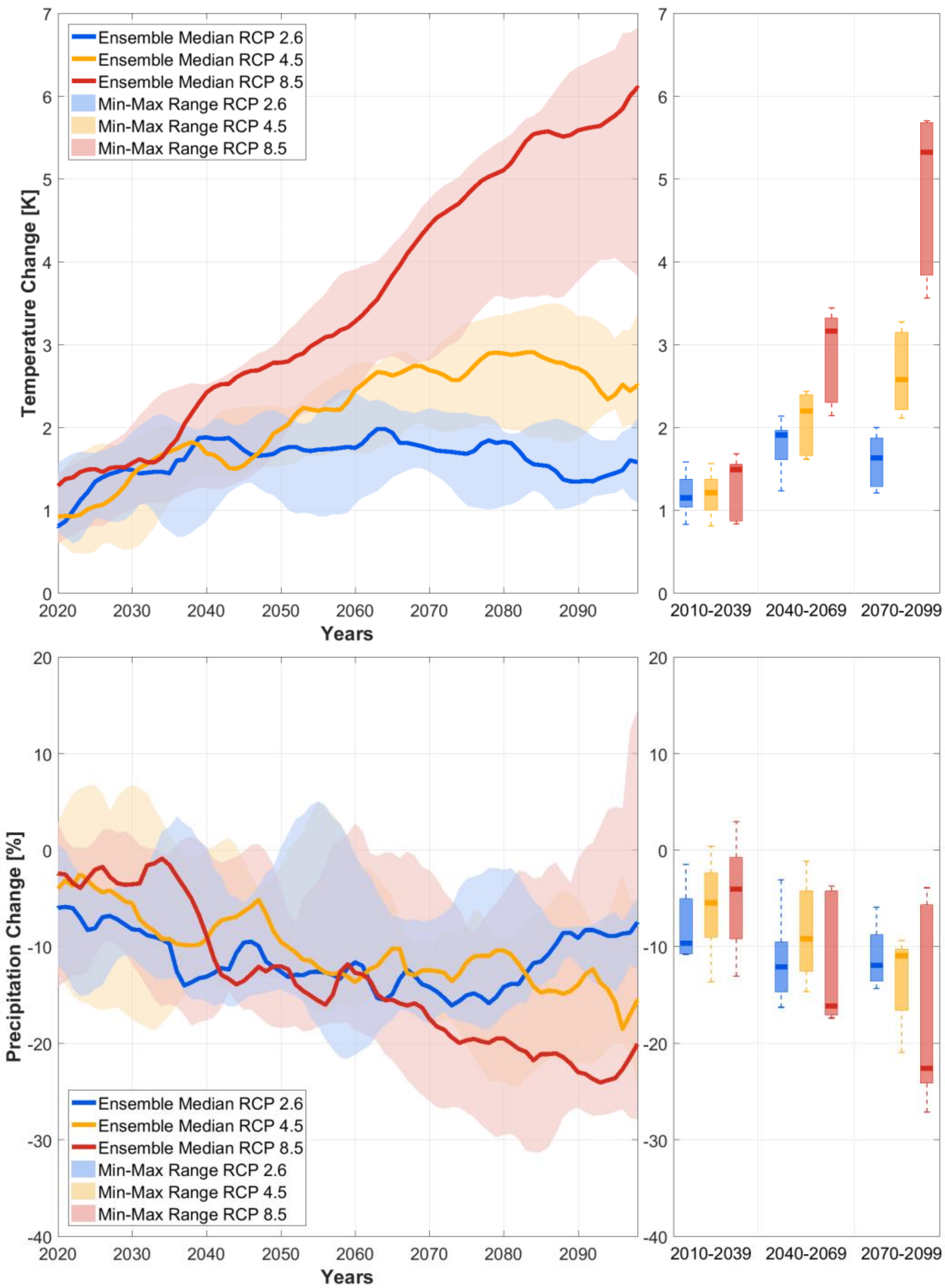

Fig. 2 Projected absolute change of near surface air temperature in Kelvin (upper) and precipitation (lower) over the statistical growing period of maize (April-September) from 2020-2099 under RCP 2.6 (blue), RCP 4.5 (orange) and RCP 8.5 (red) compared to the reference period

(1975-2004). The dark colored line shows the model median, while the light color surface shows the range of the five different driving GCMs between minimum and maximum ensemble member for each RCP. A 5a moving average is applied. The right side shows the boxplots of each of the 30a averaged values over the range of all models, illustrating the median and the interquartile range (25 to 75 percentile), while the whiskers show the highest (max) and lowest (min) 30a average value of all models

3.1 Climate change impact on rainfed yields

Figure 3 shows the temporal course of rainfed potential maize as median and min-max range of all five driving GCMs (Table 1) from 2020-2099 for RCP 2.6, RCP 4.5 and RCP 8.5. Thereby, potential maize yield decreases by 1.1%, 9.0% and 26.2% under RCP 2.6, RCP 4.5 and RCP 8.5 respectively when applying a linear regression from 2020 to 2099. The model spread is decreasing with higher RCP. The range of models is between -17.4% (MIROC5) and 17.2% (MPI-M-MPI-ESM-LR) for RCP 2.6, -29.4% (HadGEM2-ES) and -0.2% (MIROC5) for RCP 4.5 and between -37.6% (MPI-ESM) and -20.5% (NCC-NorESM1-M) for RCP 8.5.

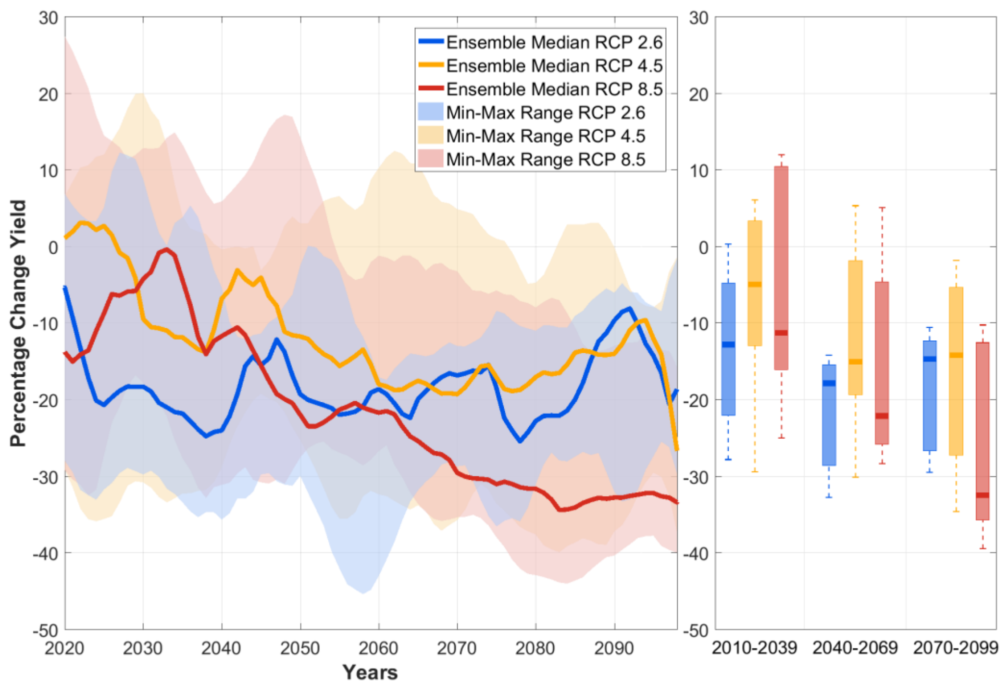

Fig. 3 Projected percentage change of rainfed maize potential yield from 2020-2099 under RCP 2.6 (blue), RCP 4.5 (orange) and RCP 8.5 (red) compared to the rainfed maize reference (1975-2004). The dark colored line shows the model median, while the light color surface shows the range of resulting yield from the five different driving GCMs between minimum and maximum ensemble member for each RCP. A 5a moving average is applied. The right side shows the boxplots of each of the 30a averaged yield over the range of all models, illustrating the median and the interquartile range (25 to 75 percentile), while the whiskers show the highest (max) and lowest (min) 30a average value of all models

Slicing the time frame into 30a climate normals (2010-2039, 2040-2069 and 2070-2099) and comparing each climate normal with the reference period (1975-2004), the right side of Fig. 3 shows the percentage change of potential rainfed maize yield under the three RCPs. Maize yield declines by 12.8%, 4.9% and 11.2% under RCP 2.6, RCP 4.5 and RCP 8.5 respectively for the time period 2010-2039 and by 17.8%, 14.9% and 22.1% under RCP 2.6, RCP 4.5 and RCP 8.5 respectively for the time period 2040-2069 and by 14.7%, 14.1% and 32.4% under RCP 2.6, RCP 4.5 and RCP 8.5 respectively for the time period 2070-2099. Thus, yields for RCP 2.6 and RCP 4.5 decrease until the middle of the century and do not further decrease until 2100, while the decrease in RCP 8.5 continuously gets stronger. This effect is even stronger for irrigated conditions (compare section 3.2). Compared with Fig. 2, also temperature does not further increase after 2060 in RCP 2.6 and 4.5.

3.2 Climate change impact on irrigated yields

Figure 4 shows the temporal course of irrigated potential maize yield from 2020-2099 for RCP 2.6, RCP 4.5 and RCP 8.5 in comparison to the rainfed reference period (1975-2004). The potential irrigated maize yield decreases by 4.3%, 23.0% and 44.5% under RCP 2.6, RCP 4.5 and RCP 8.5 respectively, but still are higher than the rainfed yield. The range of model results is between -12.9% (MIROC5) and 7.2% (MPI-M-MPI-ESM-LR) for RCP 2.6, -37.1% (HadGEM2-ES) and -17.8% (EC-EARTH) for RCP 4.5 and between -52.4% (HadGEM2-ES) and -40.4% (NCC-NorESM1-M) for RCP 8.5.

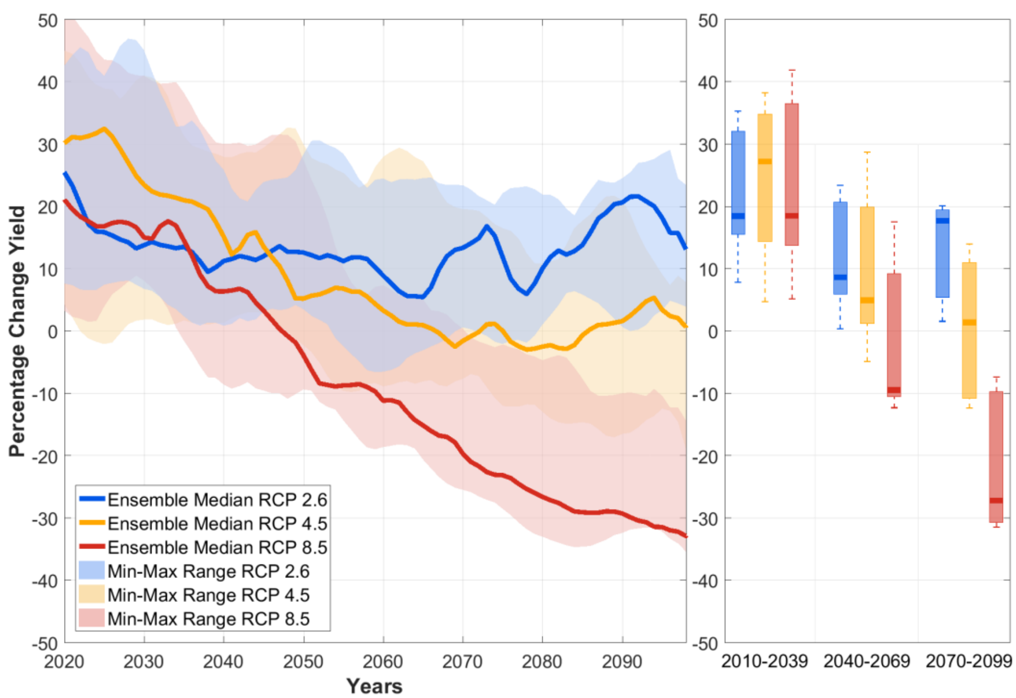

Fig. 4 Projected percentage change of irrigated maize potential yield from 2020-2099 under RCP 2.6 (blue), RCP 4.5 (orange) and RCP 8.5 (red) compared to rainfed reference maize yield (1975-

2004). The dark colored line shows the model median, while the light color surface shows the range of resulting yield from the five different driving GCMs between minimum and maximum ensemble member for each RCP. A 5a moving average is applied. The right side shows the boxplots of each of the 30a averaged yield over the range of all models, illustrating the median and the interquartile range (25 to 75 percentile), while the whiskers show the highest (max) and lowest (min) 30a average value of all models

Slicing the time frame into 30a climate normals (2010-2039, 2040-2069 and 2070-2099) and comparing each climate normal with the reference period (1975-2004). Figure 4 shows maize irrigated yield changes by +18.5%, +27.3% and +18.5% under RCP 2.6, RCP 4.5 and RCP 8.5 respectively for the time period 2010-2039 and by 8.7%, 4.9% and -9.4% under RCP 2.6, RCP 4.5 and RCP 8.5 respectively for the time period 2040-2069 and by 17.7%, 1.4% and -27.1% under RCP 2.6, RCP 4.5 and RCP 8.5 respectively for the time period 2070-2099.

Comparing Fig. 3 with Fig. 4, both relative to the rainfed reference, irrigated maize in percentage change decreases more than rainfed maize. However, irrigation still increases maize yield compared to rainfed until 2100, at least for RCP 2.6 and RCP 4.5, while for RCP 8.5 applying irrigation does not contribute to higher maize yield. Around the year 2050, irrigated maize yield will have the same magnitude than the reference rainfed yield for RCP 8.5.

3.3 Decomposition Analysis

Figure 5 shows the contributions of temperature, water stress and CO_2 on maize yield changes for all RCPs until 2070-2099. Temperature contributes to total maize yield losses by up to 85% for RCP 8.5, 67% for RCP 4.5 and 52% for RCP 2.6. This demonstrates the strong dominance of temperature stress for all RCPs in the Gambella region until the end of the century. It is the by far dominant effect responsible for yield reduction in the region, mainly in RCP 8.5. Temperature is becoming the limiting factor since crops reach its maximum temperature thresholds. On the other hand, the effect of water stress on maize yield is decreasing with higher RCPs. Water stress reduces maize yield by 43.4% for RCP 2.6, 24.1% for RCP 4.5 and 6.2 for RCP 8.5. The positive CO2 effect on maize yield was expected to be low, since maize is C4 crops. The effect is highest for RCP 8.5 (increases maize yield by 8.9%), because in this scenario also the highest CO_2 concentrations occurs.

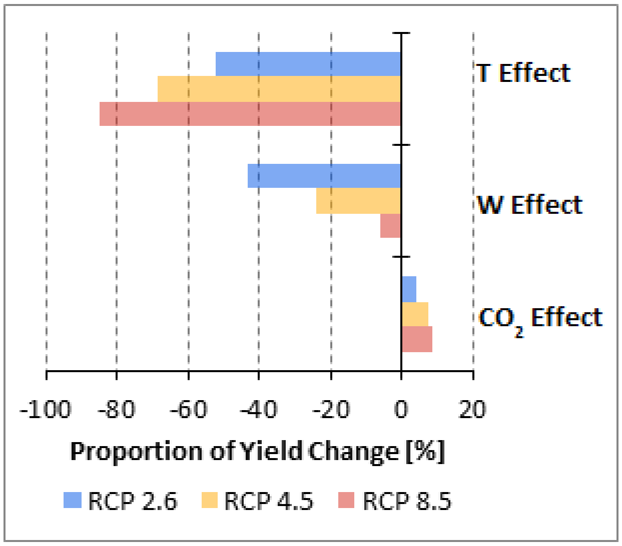

Fig. 5 Decomposition of temperature (T), water stress (W), CO_2 impacts on yield showing the proportion of each element on median maize potential yield change from the five different driving GCMs for the 30a average period 2070-2099 under RCP 2.6, RCP 4.5 and RCP 8.5

In order to get deeper understanding on how temperature increase impacts on yields, we analyze the growing days (number of days from planting to maturity) in the Gambella region. Temperature not only affects crop yields by temperature limitations of photosynthesis, but also by determining the phenological progress of crops. Thereby, crop varieties require different temperatures to reach maturity. Generally, higher temperature is associated with faster maturity that goes along with a reduced number of growing days, which usually results in lower yields (Minoli et al. 2019). Besides temperature increase, water stress is another abiotic factor that can accelerate phenology during the reproductive stage and thus also leads to faster maturity.

Figure 6 shows a clear correlation (R^2 0.81) between temperature increase and decreasing growing days for irrigated maize under RCP 8.5, without the occurrence of water stress. The shortened growing period is strongly associated with yield reductions, shown by the strong correlation (R^2 0.9) between growing days and yield, which suggests that the impact of temperature increase on the growing period has an even larger effect on yields than temperature limitations on photosynthesis.

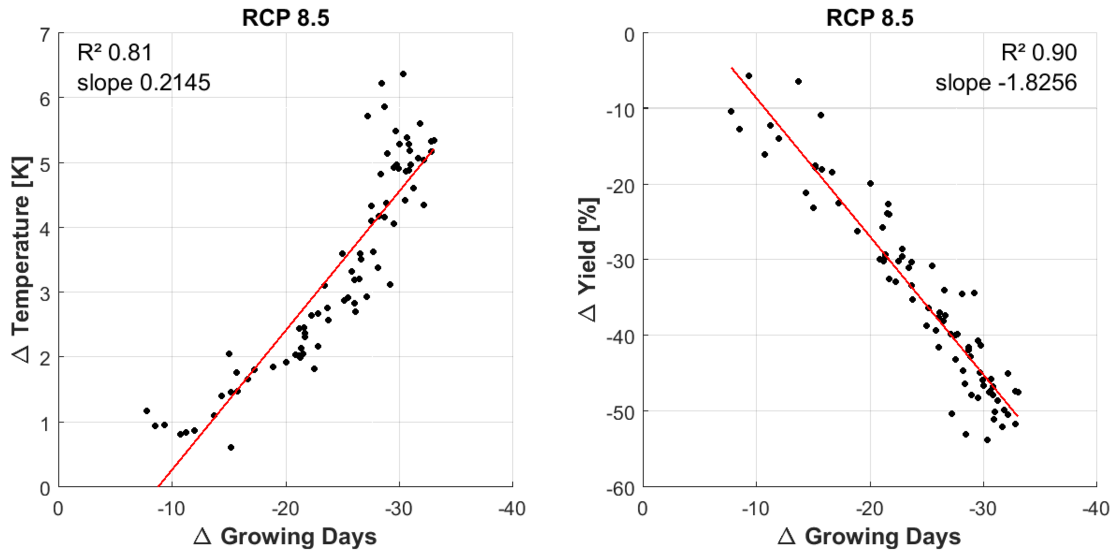

Fig. 6 Correlation between near surface air temperature and the number of irrigated maize growing days (left) and between potential irrigated maize yield and the number of irrigated maize growing days (right) for RCP 8.5 (2020-2099) in the Gambella region

For the reference period (1975-2004), the growing period was 125 days for rainfed and 132 for irrigated. As expected, the growing period is shorter with water stress in rainfed case than for irrigated case. Figure 7 shows for all RCP scenarios the projected number of growing days from 2020-2100 under rainfed and irrigated conditions. For all scenarios, the average number of growing days becomes smaller, which means earlier mature harvest. While the number of growing days is reduced by 5 days for RCP 2.6 both, for irrigated and rainfed conditions between 2070-2099 in comparison with 2010-2039, they are reduced by 15 days for RCP 8.5 in case of irrigation and 11 days in case of rainfed. Compared to the reference, the number of growing days decreases by 29 days In case of irrigation and by 23 days in case of rainfed until 2070-2099. Accordingly, the growing period is shortened more in the irrigated case than in the rainfed case, indicating that the effect of water stress on the growing period length is reduced. As visible in Fig. 7, the number of growing days between irrigated and rainfed are getting more similar until the end of the century, since temperature increase alone (without water stress) reduces the number of growing days in such a strong magnitude, that water stress occurs less frequently during the reproductive stage.

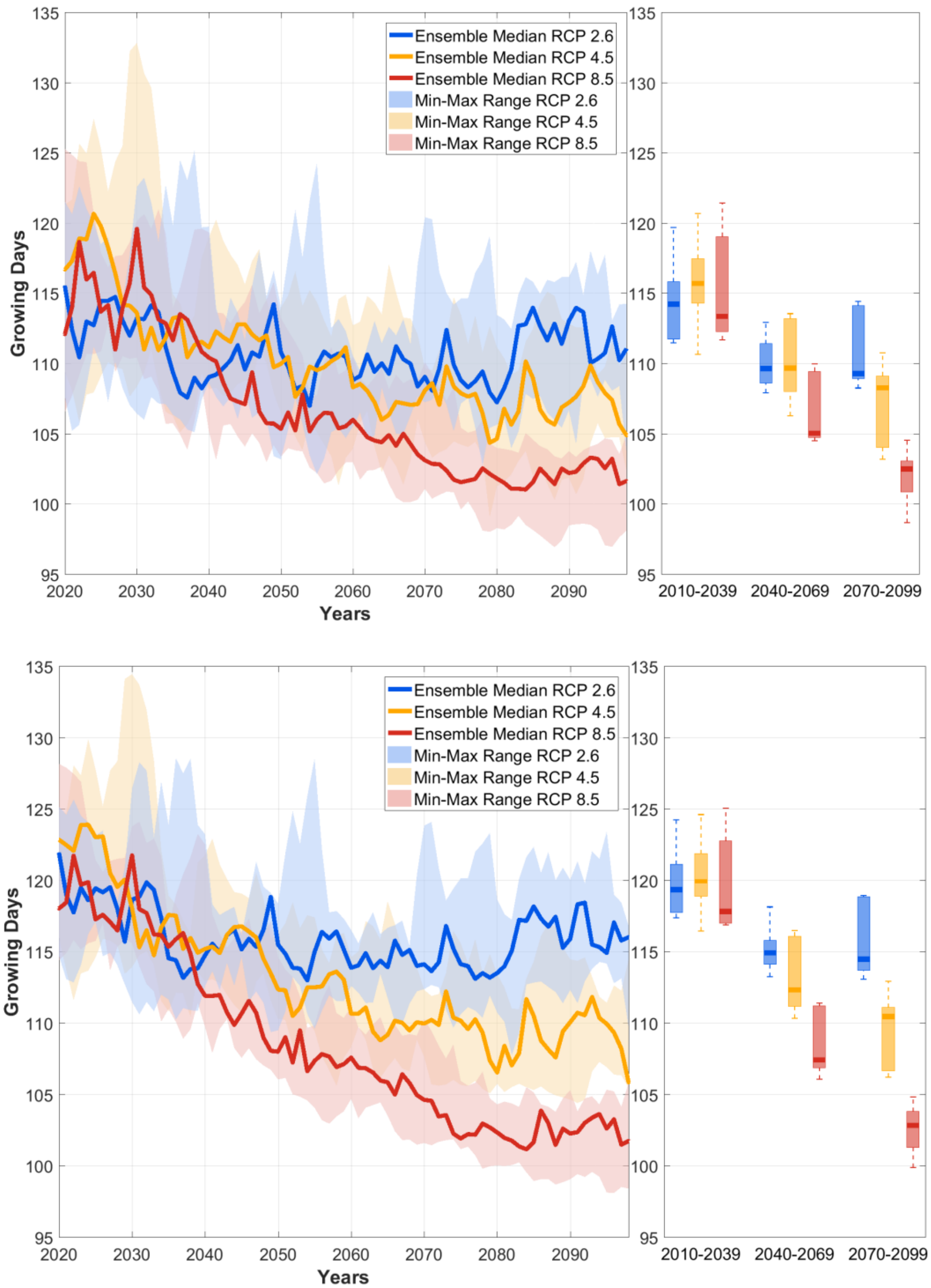

Fig. 7 Projected growing days of rainfed (upper) and irrigated (lower) maize from 2020-2099 under RCP 2.6 (blue), RCP 4.5 (orange) and RCP 8.5 (red). The dark colored line shows the model median, while the light color surface shows the range of resulting maize yield from the five different driving GCMs between minimum and maximum ensemble member for each RCP. A 5a moving average is applied. The right side shows the boxplots of each of the 30a averaged growing days over the range of all models, illustrating the median and the interquartile range (25 to 75 percentile), while the whiskers show the highest (max) and lowest (min) 30a average value of all models

4. Discussion

Agriculture is a sector that is closely linked to climate and that is thereby naturally prone to impacts of climate change (Bedeke et al. 2019; FAO 2016; Lobell et al. 2008). Therefore, the drivers of these changes must be understood to be able to propose more effective strategies for future food security (Alemu and Mengistu 2019; Najafi et al. 2018). We show in this paper the impact of climate change for different RCPs on potential maize yield in the Gambella region of Ethiopia, assuming the use of today's cropland in addition to the best 50% expansion area (Degife et al. 2019). Thereby, the RCPs describe ranges of possible future development and are selected to represent a low, medium and strong climate change signal. The results demonstrate that maize potential yield is supposed to decrease under all selected RCPs, with highest yield reductions under RCP 8.5.

Although this RCP has the highest CO_2 increase, the physiological effect of temperature increase is most dominant in this scenario, contributing to 85% of the reduction for rainfed maize yield. As we show, increasing temperature is the most contributing factor which reduces maize potential yield in the Gambella region with a prevailing tropical climate meaning already high temperature levels but also a high precipitation amounts. Thereby, increasing temperatures not only reduces the efficiency of photosynthesis, but also results in a faster development of maize crop which leads to a shorter life cycle resulting in smaller plants, shorter reproductive duration, and lower yield. These effects in summary result in less water demand of the crop and thus, although precipitation declines between 9.3% and 15.8%, reduced water stress. For this analysis, we keep the growing period fixed according to statistical data, in order to be consistent and use the same period for summing up precipitation. Given a temperature increase in Gambella by up to 6K that result in maize yield decreases by approx. 30%, our results support findings from other studies that show a reduction of yields by 5% per degree warming (Challinor et al. 2014; Hatfield et al. 2011). Our results for CO_2 responses are also in line with measurements from the Free Air CO_2 Enrichment (FACE) experiments that show positive CO_2 responses for maize by approximately 8% for a 550 ppm CO_2 enrichment and irrigated conditions (Deryng et al. 2016) corresponding approximately to the atmospheric CO_2 concentration under RCP 4.5, where our results show a positive CO_2 response by 7.4%.

Although temperature increase and shortening growing days are supposed to affect increasing incidence of diseases, pests and weeds outbreaks in Africa (Adhikari et al. 2015), it is important to note that the simulated yield decrease rates refer to potential yield, assuming perfect crop management. Despite the expected reductions of maize potential yield, intensification potentials still remain and are a major strategy for possible future production increase in the region, due to high yield gaps (Degife et al. 2019). However, our results also show that in the course of intensification, irrigation as a strategy for intensification will lose effectiveness, due to the increasing dominance of temperature stress.

Generally, our results refer to maize that provides a substantial portion of daily caloric intake in the Gambella region. Other crops may be affected differently by climate change impacts, depending on different crop physiologies and differently crop management.

Another expected impact of future climate change is an increased occurrence of extreme weather events (Gezie 2019). While other studies showed that mean climate change may lead to asymmetrical responses in the frequency and intensity of severe weather events that can cause large scale droughts, flooding or severe reduction of crop yields in the study area (Dika 2018; Regan et al. 2019; Wakuma Abaya et al. 2009), we did not consider single weather events in this study. As rainfall becomes more variable, farmers may no longer be able to rely on their knowledge of the seasonality of climatic variables. Shifting planting seasons and weather patterns will make it harder for farmers to maintain trust in planning and managing yield production (Akpodiogaga-a and Odjugo 2010; Lipper et al. 2014).

Adaptation as possible strategies to reduce climate change impacts are not considered in this study. An often discussed option is changing land-use patterns suggesting e.g. relocating cropland to higher altitudes if available. However, relocation of cropland often is associated with negative impacts on ecosystems (Zabel et al. 2019) and higher altitudes are often not well suitable for agriculture (e.g. due to high slope). Shifting sowing dates and using adapted crop varieties or different cultivars are other possible measures for adaptation. Thereby, adapted crop varieties could prolong the shortened growing periods by increasing the heat units required to reach maturity. As shown by Minoli et al. (2019) the use of such adapted varieties potentially have a high impact on crop yields and can globally compensate warming up to 2K. By doing so, irrigation and available water from precipitation could again become an important factor for intensification and possible adaptation in the Gambella region, since it is likely that adapted varieties require more water when they grow longer. For further studies, the effect of adaptive growing seasons by assuming adapted varieties in addition to shifting sowing dates should be investigated both, for rainfed and irrigated conditions.

The main challenge may be on how to incorporate available knowledge and technology for possible adaptation in the Gambella region in a process in which small scale farmers are involved.

5. Conclusion

This study analyzes climate change impacts on the local scale and therefore is beneficial for local policy and decision makers and therefore allows for developing strategies for a sustainable agricultural development within the Gambella Region under a range of possible future climate conditions. Maize is predominantly grown by smallholder farmers in the region, who mostly cultivate small parcels of land, which are often degraded. Climate change adds further challenges to the existing problems and undermines efforts that are being made to enhance food security in the region.

The strong heat response in the Gambella regions is mainly responsible for yield losses by more than 30% in case of rainfed and up to 50% in case of irrigation until the end of the century. Thereby, temperature increase is becoming the dominating effect over time and with higher RCP scenario, resulting in a decreasing role of water stress in context of yield reduction. Consequently, irrigation will lose effectiveness for increasing yields when temperature becomes the limiting factor. Providing new varieties from breeding could be a great benefit for the region. Thereby, our results suggest that new varieties with higher growing degree days until maturity are primarily required for the Gambella region under future climate conditions.

Acknowledgements

Azeb W. Degife acknowledges financial support of the German Academic Exchange Service (DAAD) to pursue doctoral degree in Germany.

Reference

Abera K, Crespo O, Seid J, Mequanent F (2018) Simulating the impact of climate change on maize production in Ethiopia, East Africa. Environmental Systems Research 7:4

Adhikari U, Nejadhashemi AP, Woznicki SA (2015) Climate change and eastern Africa: a review of impact on major crops. Food and Energy Security 4:110-132

Akpodiogaga-a P, Odjugo O (2010) General overview of climate change impacts in Nigeria. Journal of Human Ecology 29:47-55

Alemu T, Mengistu A (2019) Impacts of Climate Change on Food Security in Ethiopia: Adaptation and Mitigation Options: A Review. In: Climate Change-Resilient Agriculture and Agroforestry. Springer, pp 397-412

Alemu Z, Oosthuizen K, Van Schalkwyk H (2003) Contribution of agriculture in the Ethiopian economy: a time-varying parameter approach. Agrekon 42:29-48

Aragie EA (2013) Climate change, growth, and poverty in Ethiopia. Texas Univ at Austin

Ball JT, Woodrow I, Berry J (1987) A Model Predicting Stomatal Conductance and its Contribution to the Control of Photosynthesis under Different Environmental Conditions. In: Biggins J (ed) Progress in Photosynthesis Research. Springer Netherlands, pp 221-224. doi:10.1007/978-94-017-0519-6_48

Barbier EB, Hochard JP (2018) The impacts of climate change on the poor in disadvantaged regions. Review of Environmental Economics and Policy 12:26-47

Bedeke S, Vanhove W, Gezahegn M, Natarajan K, Van Damme P (2019) Adoption of climate change adaptation strategies by maize-dependent smallholders in Ethiopia. NJAS-Wageningen Journal of Life Sciences 88:96-104

Belloumi M (2014) Investigating the impact of climate change on agricultural production in eastern and southern African countries vol 3. Intl Food Policy Res Inst

Bryan E, Deressa TT, Gbetibouo GA, Ringler C (2009) Adaptation to climate change in Ethiopia and South Africa: options and constraints. Environmental science & policy 12:413-426

Central Statistical Agency (2017) Agricultural sample survey area and production of major crops vol 1. Ministry of Agriculture Ethiopia, Addis Ababa, Ethiopia

Challinor AJ, Watson J, Lobell DB, Howden SM, Smith DR, Chhetri N (2014) A meta-analysis of crop yield under climate change and adaptation. Nat Clim Change 4:287-291. doi:10.1038/nclimate2153

Cochrane L (2018) Food Security in Ethiopia: Review of Research, 2005-2016. Ethiop J Appl Sci Technol 9:1-10

Degife AW, Zabel F, Mauser W (2019) Land Use Scenarios and Their Effect on Potential Crop Production: The Case of Gambella Region, Ethiopia. Agriculture 9:105

Delzeit R, Zabel F, Meyer C, Václavík T (2017) Addressing future trade-offs between biodiversity and cropland expansion to improve food security. Regional Environmental Change 17:1429-1441. doi:10.1007/s10113-016-0927-1

Deryng D et al. (2016) Regional disparities in the beneficial effects of rising CO2 concentrations on crop water productivity. Nature Clim Change 6:786-790. doi:10.1038/nclimate2995

Diffenbaugh NS, Burke M (2019) Global warming has increased global economic inequality. Proceedings of the National Academy of Sciences 116:9808-9813

Dika G (2018) Impacts of Climate Variability and Households Adaptation Strategies in Lare District of Gambella Region, South Western Ethiopia. J Earth Sci Clim Change 9:2

Dosio A, Panitz H-J (2016) Climate change projections for CORDEX-Africa with COSMO-CLM regional climate model and differences with the driving global climate models. Climate Dynamics 46:1599-1625. doi:10.1007/s00382-015-2664-4

Endalew B, Muche M, Tadesse S (2015) Assessment of food security situation in Ethiopia: A Review. Asian Journal of Agricultural Research 9:55-68

FAO (2016) The state of food and agriculture. international cooperation 10:0

FAO (2017) The future of food and agriculture–Trends and challenges. FAO Rome

Farquhar GD, Caemmerer S, Berry JA (1980) A biochemical model of photosynthetic CO2 assimilation in leaves of C3 species. Planta 149:78-90. doi:10.1007/BF00386231

Fick SE, Hijmans RJ (2017) WorldClim 2: new 1-km spatial resolution climate surfaces for global land areas. International Journal of Climatology 37:4302-4315. doi:10.1002/joc.5086

Gbegbelegbe S, Chung U, Shiferaw B, Msangi S, Tesfaye K (2014) Quantifying the impact of weather extremes on global food security: A spatial bio-economic approach. Weather and Climate Extremes 4:96-108

Gezie M (2019) Farmer's response to climate change and variability in Ethiopia: A review. Cogent Food & Agriculture 5:1613770

Hallegatte S, Fay M, Barbier EB (2018) Poverty and climate change: introduction. Environment and Development Economics 23:217-233

Hank TB, Bach H, Mauser W (2015) Using a Remote Sensing-Supported Hydro-Agroecological Model for Field-Scale Simulation of Heterogeneous Crop Growth and Yield: Application for Wheat in Central Europe. Remote Sensing 7:3934-3965. doi:10.3390/rs70403934

Hatfield JL et al. (2011) Climate impacts on agriculture: implications for crop production. Agronomy journal 103:351-370

Iizumi T et al. (2017) Responses of crop yield growth to global temperature and socioeconomic changes. Scientific reports 7:7800

IPCC (2013) Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, United Kingdom and New York, NY, USA

IPCC (2014) Climate change 2014: synthesis report. Geneva, Switzerland

Kassie B, Rötter R, Hengsdijk H, Asseng S, Van Ittersum M, Kahiluoto H, Van Keulen H (2014) Climate variability and change in the Central Rift Valley of Ethiopia: challenges for rainfed crop production. The Journal of Agricultural Science 152:58-74

Leal Filho W, Simane B, Kalangu J, Wuta M, Munishi P, Musiyiwa K (2017) Climate change adaptation in Africa. Springer

Lipper L et al. (2014) Climate-smart agriculture for food security. Nature climate change 4:1068

Lobell DB, Burke MB, Tebaldi C, Mastrandrea MD, Falcon WP, Naylor RL (2008) Prioritizing climate change adaptation needs for food security in 2030. Science 319:607-610

Marke T, Mauser W, Pfeiffer A, Zängl G, Jacob D, Strasser U (2014) Application of a hydrometeorological model chain to investigate the effect of global boundaries and downscaling on simulated river discharge. Environ Earth Sci 71:4849-4868. doi:10.1007/s12665-013-2876-z

Mauser W, Klepper G, Zabel F, Delzeit R, Hank T, Putzenlechner B, Calzadilla A (2015) Global biomass production potentials exceed expected future demand without the need for cropland expansion. Nat Commun 6. doi:10.1038/ncomms9946

Mekonnen DA, Gerber N (2017) Aspirations and food security in rural Ethiopia. Food security 9:371-385

Minoli S et al. (2019) Global response patterns of major rainfed crops to adaptation by maintaining current growing periods and irrigation. Earth's Future 0. doi:10.1029/2018ef001130

Najafi E, Devineni N, Khanbilvardi RM, Kogan F (2018) Understanding the changes in global crop yields through changes in climate and technology. Earth's Future 6:410-427

Niang I, Ruppel O, Abdrabo M, Essel A, Lennard C, Padgham J, Urquhart P (2014) Africa Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change Cambridge Univ Press, Cambridge, UK, United Kingdom and New York, NY, USA

Parry ML, Rosenzweig C, Iglesias A, Livermore M, Fischer G (2004) Effects of climate change on global food production under SRES emissions and socio-economic scenarios. Global environmental change 14:53-67

Porter JR et al. (2014) Food security and food production systems. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability.Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, United Kingdom and New York, NY, USA,

Regan PM, Kim H, Maiden E (2019) Climate change, adaptation, and agricultural output. Regional environmental change 19:113-123

Seleshi Y, Zanke U (2004) Recent changes in rainfall and rainy days in Ethiopia. International Journal of Climatology: A Journal of the Royal Meteorological Society 24:973-983

Shiferaw A (2017) Productive capacity and economic growth in Ethiopia. United Nations, Department of Economics and Social Affairs

Shiferaw A, Tadesse T, Rowe C, Oglesby R (2018) Precipitation extremes in dynamically downscaled climate scenarios over the greater horn of Africa. Atmosphere 9:112

Tadesse M (2007) Gambella The Impact of Local Conflict On Regional Security. Institute for Security Studies (ISS), Addis Ababa, Ethiopia

Tesfaye K, Seid J, Getnet M, Mamo G (2016) Agriculture under a Changing Climate in Ethiopia: Challenges and Opportunities for Research. Ethiopian Journal of Agricultural Sciences

Van Vuuren DP et al. (2011) The representative concentration pathways: an overview. Climatic change 109:5

Wakuma Abaya S, Mandere N, Ewald G (2009) Floods and health in Gambella region, Ethiopia: a qualitative assessment of the strengths and weaknesses of coping mechanisms. Global health action 2:2019

Woube M (1999) Flooding and sustainable land–water management in the lower Baro–Akobo river basin, Ethiopia. Applied Geography 19:235-251

Wubie AA (2015) Review on the Impact of Climate Change on Crop Production in Ethiopia. Journal of Biology, Agriculture and Healthcare 5:103-111

Xinyou Y, Van Laar H (2005) Crop systems dynamics: an ecophysiological simulation model for genotype-by-environment interactions. Wageningen Academic Pub

Zabel F, Delzeit R, Schneider JM, Seppelt R, Mauser W, Václavík T (2019) Global impacts of future cropland expansion and intensification on agricultural markets and biodiversity. Nature Communications 10:2844. doi:10.1038/s41467-019-10775-z

Zabel F, Putzenlechner B, Mauser W (2014) Global agricultural land resources–a high resolution suitability evaluation and its perspectives until 2100 under climate change conditions. PloS one 9:e107522

Zerga B, Gebeyehu G (2016) Climate Change in Ethiopia Variability, Impact, Mitigation, and Adaptation. Journal of Social Science and Humanities Research 2:66-84

7. Conclusion

From the overall research findings, some important conclusions can be drawn. In the Gambella resettlement program, demographic growth and large-scale land investment has caused enormous LULCC in the region. Tropical grasslands had the largest share in 1987, representing 53.74% of the total LULC categories assigned in the region. This class underwent a major shift and was reduced to 41.94% and 35.70% in 2000 and 2017, respectively. The other class that declined was forest land, reducing from 16.41% in 1987 to 15.50% in 2017. Over the last 30 years, cropland expansion (large- and small-scale farming) mainly took place at the expanse of tropical grassland and forest areas. In total, about 202km^2 of cultivated area was identified as large-scale commercial farmland in 1987 and it had increased to 746km^2 in 2017. Between 1987–2017, agricultural area increased by 27% of the area change in the Gambella region. The Gambella National Park, which is one of the nation's largest national parks, has been affected by farmland/cropland expansion, mainly by large-scale farm activities. The conversion of tropical grasslands and forest land to large-scale farmland has caused extensive environmental degradation in the Gambella National Park, and major negative outcomes for local people's livelihoods.

In order to establish sustainable crop production in the region, a systematic exploration of the potential for agricultural intensification and cropland expansion scenarios was carried out. The expansion takes place in the highest-yielding 30% (TOP 30) and 50% (TOP 50) of the feasible rangeland in the area and different intensification options ranging from low-input rainfed agriculture through high-input rainfed agriculture to high-input irrigated agriculture. The combination of the assumptions in expansion and intensification leads to six scenarios: Low-Input Rainfed (LIR 30 and LIR 50), High-Input Rainfed (HIR 30 and HIR 50) and High-Input Irrigated (HII 30 and HII 50). The average potential yield of maize and sorghum in the HIR 30 scenarios is 7.5 t ha^{-1} and 4.0 t ha^{-1}, respectively. In HII 30, irrigation increases the average maize and sorghum yields to 7.7 t ha^{-1} and 4.3 t ha^{-1}, respectively. The average yield of maize and sorghum in HIR 30 and HIR 50, as also in HII 30 and HII 50, does not show any significant difference.

Regarding average yield production, maize and sorghum is increased by 350% and 300% in the LIR 30 compared to the average maize and sorghum yield reference production. In the HIR 30, average maize and sorghum production is increased by 1,000% and 700%, respectively, compared to the average maize and sorghum yield reference production. In the HII 30, average maize and sorghum production is increased by 1,025% and 733%, respectively. The total simulation potential production of HIR and HII in the region does not reflect any significant difference, which implies that the annual rainfall of the region is enough for crop production. Under current climate conditions, Gambella's agricultural potential by far exceeds the caloric demands of its people. For instance, within the LIR 30, Gambella's agriculture could supply the necessary calories for 6.6 million people and it would further increase to 15.0 million in the HIR 30 scenario by assuming a daily diet of 2200 kcal/cap/day. In HIR 50 and HII 50, on the other hand, the number of people that can be fed increases by 21.0 and 21.3 million, respectively. The region could theoretically go on without cropland expansion, securing food supply for its current and future population and preserving natural resources like biodiversity, water resources and soil fertility for the demand of future generations. The potentials, if exploited, would additionally allow for the exportation of food resources from Gambella to the national and international markets.

Nevertheless, under a range of possible future climate conditions, the potential of maize yield in rainfed agriculture decreases by 1.1%, 9.0% and 26.2% under RCP 2.6, 4.5 and 8.5, respectively, when applying a linear regression from 2020–2099. On the other hand, potential irrigated maize yield decreases by 4.3%, 23.0% and 44.5% under RCP 2.6, 4.5 and 8.5, respectively. Soil water availability and temperature increase have negative effects on the simulated maize yield potential. Water stress reduces maize yield by 43.4% for RCP 2.6, 24.1% for RCP 4.5, and 6.2% for RCP 8.5. Similarly, temperature contributes to total maize yield losses by up to 85% for RCP 8.5, 67% for RCP 4.5, and 52% for RCP 2.6 until the end of the century. Temperature increase not only affects crop yields but also the faster maturity that goes along with a shortened growing period. For all scenarios, the average number of growing days becomes smaller. Compared to the reference (actual statistic data), the number of growing days decreases by 29 days in the irrigation case and by 23 days in the rainfed case between 2070–2099. At the end of the century, the effect of water stress on the growing period length will have declined but the effect of temperature will have increased, and will be strong. Particularly with the higher RCP scenario, the effect of temperature becomes more severe. Thereby, new varieties with higher growing degree days until maturity are primarily required for the Gambella region under future climate conditions in order to secure potential crop production for the future generation. Furthermore, local policy- and decision-makers could develop strategies for a sustainable agricultural development within the Gambella region under a range of possible future climate conditions.

8. Outlook

- This study advocates the use of multi-temporal and high-resolution satellite data to detect and assess changes in LULC comprehensively. This could further be investigated by local field work and the compilation of additional sources can enable the observed changes to be put into a larger perspective to be able, finally, to understand the LULC dynamics and to formulate successful LU strategies in the Gambella region.
- Calculating the rate, extent and distribution of LULC classification for Gambella region from 1987–2017 has been done using multi-temporal and high-resolution satellite data. However, some fundamental researches would be a possible next step in further studies, such as land suitability classification and agricultural land suitability evaluation for crop production (Zabel, Putzenlechner et al. 2014, Yitbarek, Beyene et al. 2016, Yitbarek, Kibret et al. 2017). This could improve proper agricultural investment in the region.
- LULC classification shows large-scale agricultural activities and strong human interferences within the protected Gambella National Park. This could further be investigated by investigating the environmental impacts of the effects of certain public and private agricultural projects within the park (Girma and Beyene 2015, Aneseyee 2016, David Ambrosetti 2016).
- Large-scale and small-scale farming intensity has been identified in terms of use of machinery and fertilizer, as well as pesticide application related to field size. In addition, high-resolution satellite images and Google Earth were used as a reference. However, small-scale farming distribution of crops is often extremely heterogeneous, meaning

large uncertainties in the spatial distribution. Thus, further studies are required at high-resolution in combination with field data to get better information on farming intensity and crop distributions at the field scale across smallholders in the region.

- The cropland expansion does not consider utilizing any legally protected land for expansion, and does not consider distributions of endemic richness and biodiversity. Since this study has only considered those areas best-suited for expansion, further investigations are necessary to determine whether these identified best expansion areas are important for biodiversity or other ecosystem service functions and, consequently, whether they should be protected and preserved.
- Agriculture is prone to climate change impacts. Therefore, adaptation is a required strategy to reduce climate change impacts on agricultural activities. However, this study does not consider adaptation strategies. For further studies, the effect of adaptive growing seasons by assuming adapted varieties in addition to shifting sowing dates should be investigated for both rainfed and irrigated conditions.

9. References

Abbade, E. B. (2017). "Availability, access and utilization: Identifying the main fragilities for promoting food security in developing countries." World Journal of Science, Technology and Sustainable Development **14**(4): 322-335.

Abera, K., O. Crespo, J. Seid and F. Mequanent (2018). "Simulating the impact of climate change on maize production in Ethiopia, East Africa." Environmental Systems Research **7**(1): 4.

Admassie, A. and D. Abebaw (2014). Rural poverty and marginalization in Ethiopia: a review of development interventions. Marginality, Springer**:** 269-300.

Admassie, A., B. Assefa and K. Descheemaeker (2017). Reducing The Maize Yield Gap In Ethiopia: Analysis And Policy Simulation. Addis Ababa,Ethiopia, Economic & Social Research Council (E.S.R.C) and Department for International Development (DFID)**:** 1-4.

Alemayehu, Y., H. Gebrekidan and S. Beyene (2014). "Pedological characteristics and classification of soils along landscapes at Abobo, southwestern lowlands of Ethiopia." Journal of Soil Science and Environmental Management **5**(6): 72-82.

Alemu, G. T., Z. Berhanie Ayele and A. Abelieneh Berhanu (2017). "Effects of Land Fragmentation on Productivity in Northwestern Ethiopia." Advances in Agriculture **2017**: 1-9.

Alemu, M. M. and F. Y. Desta (2017). "Seasonal rainfall and crop productivity in South West Ethiopia: Preliminary analysis for recent climate." International Journal of Water Resources and Environmental Engineering **9**(10): 211-217.

Alemu, T. and A. Mengistu (2019). Impacts of Climate Change on Food Security in Ethiopia: Adaptation and Mitigation Options: A Review. Climate Change-Resilient Agriculture and Agroforestry, Springer**:** 397-412.

Aneseyee, A. B. (2016). "Vegetation composition and deforestation impact in Gambella National Park, Ethiopia." J. Energy Nat. Resour **5**(3): 30-36.

Aragie, E. (2013). Climate change, growth, and poverty in Ethiopia. The Robert Strauss Center for International Security and Law. Climate Change and African Political Stability (CCAPS) Austin , Texas, University of Texas at Austin**:** 1-28.

Awoke, Z., B. Teferi and T. Mekonen (2018). "Impacts of Resettlement on Woodland Resource Utilization in Abobo Wereda, Gambella, Ethiopia." Journal of Resources Development and Management **41**(4): 67-77.

Baumgartner, P. W. (2017). The Impacts of Large-scale Land-acquisition in East Africa on Poverty Reduction and the Rural Economy: Studies in Ethiopia and Uganda. Dr.agr. monography, Rheinische Friedrich-Wilhelms-Universität Bonn.

Baye, T. G. (2017). "Poverty, peasantry and agriculture in Ethiopia." Annals of Agrarian Science **15**(3): 420-430.

Bewket, W. (2009). Rainfall variability and crop production in Ethiopia: Case study in the Amhara region. Proceedings of the 16th International Conference of Ethiopian Studies, Norwegian University of Science and Technology Trondheim, Norway.

Bewket, W., M. A. Radeny and C. Mungai (2015). Agricultural adaptation and institutional responses to climate change vulnerability in Ethiopia Working Paper no. 106. Copenhagen, Denmark, CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS).

Bezu, S. and S. Holden (2014). "Are rural youth in Ethiopia abandoning agriculture?" World Development **64**: 259-272.

Braun, J. V. and F. W. Gatzweiler (2014). Marginality: Addressing the nexus of poverty, exclusion and ecology. Marginality—An Overview and Implications for Policy. J. V. Braun and F. W. Gatzweiler. Dordrecht Heidelberg New York London, Springer**:** 1-26.

Brhane Meles Gebre & Zemenu Awoke Andualem (2018). "Impacts of Resettlement on Land Use Land Cover Changes and Natural Vegetation Conservation Practices of Resettlers in Abobo Woreda, Gambella, Ethiopia." Journal of Resources Development and Management **40**: 20-28.

Brown, M. E., C. Funk, D. Pedreros, D. Korecha, M. Lemma, J. Rowland, E. Williams and J. Verdin (2017). "A climate trend analysis of Ethiopia: examining subseasonal climate impacts on crops and pasture conditions." Climatic change **142**(1-2): 169-182.

Cascão, A. E. (2013). Resource-based conflict in South Sudan and Gambella (Ethiopia): When water, land and oil mix with politics. State and Societal Challenges in the Horn of Africa: Conflict and processes of state formation, reconfiguration and disintegration. Lisbon, University Institute of Lisbon**:** 143-165.

CSA (2018). THE 2015/16 ETHIOPIAN HOUSEHOLD CONSUMPTION – EXPENDITURE (HCE) SURVEY RESULTS FOR: GAMBELLA REGION. Addis Ababa.

CSA (2018). Population Projection of Ethiopia for All Regions At Wereda Level from 2014 – 2017. Addis Ababa,Ethiopia, Central Statistical Agency.

David Ambrosetti, J.-R. B., Deresse Ayenachew and Thomas Guindeuil (2016). Climatic and Environmental Challenges: Learning from the Horn of Africa. Addis-Abeba, Centre français des études éthiopiennes.

DeFries, R. and C. Rosenzweig (2010). "Toward a whole-landscape approach for sustainable land use in the tropics." Proceedings of the National Academy of Sciences **107**(46): 19627-19632.

Degife, A. W. and W. Mauser (2017). "Socio-economic and Environmental Impacts of Large-Scale Agricultural Investment in Gambella Region, Ethiopia." Journal of US-China Public Administration **14**(4): 183-197.

Degife, A. W., F. Zabel and W. Mauser (2018). "Assessing land use and land cover changes and agricultural farmland expansions in Gambella Region, Ethiopia, using Landsat 5 and Sentinel 2a multispectral data." Heliyon **4**(11): e00919.

Degife, A. W., F. Zabel and W. Mauser (2019). "Land Use Scenarios and Their Effect on Potential Crop Production: The Case of Gambella Region, Ethiopia." Agriculture **9**(5): 105.

Demeke, M., F. Guta and T. Ferede (2004). Agricultural development in Ethiopia: are there alternatives to food aid? Addis Ababa,Ethiopia, Addis Ababa University 1-74.

Demeke, M., F. Guta and T. Ferede (2006). Agricultural development and food security in sub-Saharan Africa (SSA). Building a Case for more Public Support The Case of Ethiopia. Rome, Italy, FAO**:** 1-81.

Dika, G. (2018). "Impacts of Climate Variability and Households Adaptation Strategies in Lare District of Gambella Region, South Western Ethiopia." J. Earth Sci. Clim. Chang **9**(2).

Dorosh, P. and S. Rashid (2013). Food and agriculture in Ethiopia: Progress and policy challenges. IFPRI issue brief. Washington, DC, University of Pennsylvania Press**:** 1-4.

Endalew, B., M. Muche and S. Tadesse (2015). "Assessment of food security situation in Ethiopia: A Review." Asian Journal of Agricultural Research **9**(2): 55-68.

FAO (2008). Climate change and food security: a framework document. Rome,Italy, FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS**:** 1-93.

FDRE (2019). Ethiopia’s Climate Resilient Green Economy National Adaptation Plan. E. s. N. A. P. (NAP-ETH). Addis Ababa, Federal Democratic Republic of Ethiopia.

Fenta, K. (2014). "Industry and Industrialization in Ethiopia: Policy Dynamics and Spatial Distributions." European Journal of Business and Management **6**(34): 326-344.

Gálvez-Nogales, E. and J. Fonseca (2014). Institutional Procurement of Staples from Smallholders: . The case of Purchase for Progress in Ethiopia. Rome,Italy, FAO**:** 1-45.

Gashaw, T., A. Bantider and A. Mahari (2014). "Evaluations of land use/land cover changes and land degradation in Dera District, Ethiopia: GIS and remote sensing based analysis." International Journal of Scientific Research in Environmental Sciences **2**(6): 199.

Gebreselassie, S., O. K. Kirui and A. Mirzabaev (2016). Economics of land degradation and improvement in Ethiopia. Economics of land degradation and improvement–a global assessment for sustainable development, Springer, Cham**:** 401-430.

Gebresenbet, F. (2016). "Land Acquisitions, the politics of dispossession, and state-remaking in Gambella, western Ethiopia." Africa Spectrum **51**(1): 5-28.

Gezie, M. (2019). "Farmer’s response to climate change and variability in Ethiopia: A review." Cogent Food & Agriculture **5**(1): 1613770.

Gibbs, H. K., A. S. Ruesch, F. Achard, M. K. Clayton, P. Holmgren, N. Ramankutty and J. A. Foley (2010). "Tropical forests were the primary sources of new agricultural land in the 1980s and 1990s." Proceedings of the National Academy of Sciences **107**(38): 16732-16737.

Gil, J. D. B., P. Reidsma, K. Giller, L. Todman, A. Whitmore and M. van Ittersum (2019). "Sustainable development goal 2: Improved targets and indicators for agriculture and food security." Ambio **48**(7): 685-698.

Girma, W. and F. Beyene (2015). "Institutional challenges in sustainable forest management: evidence from the Gambella Regional State of western Ethiopia." Journal of Sustainable Forestry **34**(3): 233-258.

Girmay, G. (2015). "Smallholder subsistence agriculture: why Ethiopia is still here." Am Res J Agric Orig Artic **1**(3): 2015.

Hamza, I. and A. Iyela (2012). "Land use pattern, climate change, and its implication for food security in Ethiopia: a review." Ethiopian Journal of Environmental Studies and Management **5**(1): 26-31.

Henry, R., K. Engström, S. Olin, P. Alexander, A. Arneth and M. Rounsevell (2018). "Food supply and bioenergy production within the global cropland planetary boundary." PloS one **13**(3): e0194695.

Hillocks, R. (2014). "Addressing the yield gap in Sub-Saharan Africa." Outlook on AGRICULTURE **43**(2): 85-90.

IMF (2016). Regional economic outlook Sub-Saharan Africa Multispeed Growth. Washington, D.C, USA, economic and financial surveys**:** 1-76.

IPCC (2014). Climate change 2014: synthesis report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change R.K. Pachauri and L.A. Meyer. Geneva, Switzerland**:** 151.

IPCC (2014). The IPCC's Fifth Assessment Report–What's in it for Africa. Climate & Development Knowledge Network (CDKN). E. Carabine, A. Lemma, M. Dupar et al.**:** 1-33.

Kahiluoto, H. and R. Rötter (2009). Implications of and possible responses to climate change. Helsinki,Finland, Department of Economics and Management,University of Helsinki**:** 1-29.

Keeley, J., W. M. Seide, A. Eid and A. L. Kidewa (2014). Large-scale land deals in Ethiopia Scale, trends, features and outcomes to date. London, Full Spectrum Print Media**:** 62.

Kelbore, Z. G. (2012). An analysis of the impacts of climate change on crop yield and yield variability in Ethiopia. Trento,Italy, University of Trento**:** 1-45.

Kottek, M., J. Grieser, C. Beck, B. Rudolf and F. Rubel (2006). "World map of the Köppen-Geiger climate classification updated." Meteorologische Zeitschrift **15**(3): 259-263.

Lewis, K. (2017). "Understanding climate as a driver of food insecurity in Ethiopia." Climatic Change **144**(2): 317-328.

Moreda, T. (2018). "The right to food in the context of large-scale land investment in Ethiopia." Third World Quarterly **39**(7): 1326-1347.

Parry, M. L., C. Rosenzweig, A. Iglesias, M. Livermore and G. Fischer (2004). "Effects of climate change on global food production under SRES emissions and socio-economic scenarios." Global environmental change **14**(1): 53-67.

Rahmato, D. (2011). Land to investors: Large-scale land transfers in Ethiopia, African Books Collective.

Schneider, K. and L. Anderson (2010). "Yield gap and productivity potential in Ethiopian agriculture: Staple grains & pulses." EPAR Brief **98**.

Se, A. S. T., P. Dorosh and S. A. Gemessa (2012). "Crop production in Ethiopia: Regional patterns and trends." Food and agriculture in Ethiopia: Progress and policy challenges **74**: 53.

Seo, K. and N. Rodriguez (2012). "Land grab, food security and climate change: a vicious circle in the Global South." Human and Social Dimensions of Climate Change: 165-180.

Sewnet, Y., E. Elemo and D. Derso (2016). "A review of agricultural research, extension and farmers linkage in Ethiopia." Agric. Biol. JN Am **7**(3): 116-120.

Stellmacher, T. and G. Kelboro (2019). "Family Farms, Agricultural Productivity, and the Terrain of Food (In) security in Ethiopia." Sustainability **11**(18): 4981.

Suryabhagavan, K. (2017). "GIS-based climate variability and drought characterization in Ethiopia over three decades." Weather and climate extremes **15**: 11-23.

Tadesse, M. (2007). Gambella The Impact of Local Conflict On Regional Security. Researching local conflicts and regional security. (Tshwane) Pretoria, South Africa**:** 1-33.

Taffesse, A. S., P. Dorosh and S. Asrat (2012). Crop production in Ethiopia: Regional patterns and trends. Summary of ESSP II Working Paper 16, “Crop Production in Ethiopia: Regional Patterns and Trends. Addis Ababa,Ethiopia, INTERNATIONAL FOOD POLICY RESEARCH INSTITUTE.

Temesgen, G., B. Amare and H. Silassie (2014). "Land degradation in Ethiopia: causes, impacts and rehabilitation techniques." Journal of environment and earth science **4**(9): 98-104.

Tilahun, U. (2014). "Review of Challenges and Prospects of Agricultural Production and Productivity in Ethiopia." Journal of Natural Sciences Research **4**(18): 70-77.

Wubie, A. A. (2015). "Review on the Impact of Climate Change on Crop Production in Ethiopia." Journal of Biology, Agriculture and Healthcare **5**(13): 103-111.

Yitbarek, T., S. Beyene and K. Kibret (2016). "Characterization and classification of soils of Abobo Area, Western Ethiopia." Applied and Environmental Soil Science **2016**: 1-16.

Yitbarek, T., K. Kibret and S. Beyene (2017). "Physical Land Suitability Evaluation for Irrigation in the Lower Alwero River Area of Abobo, Western Ethiopia." American Journal of Agriculture and Forestry **5**(3): 60.

Zabel, F., B. Putzenlechner and W. Mauser (2014). "Global agricultural land resources–a high resolution suitability evaluation and its perspectives until 2100 under climate change conditions." PloS one **9**(9): e107522.

10. Curriculum Vitae

Personal data	
Name:	Azeb W. Degife
Place of birth	Addis Ababa, Ethiopia
Degree:	M.A (Phys.Geography) and M.Sc. (Env. Science)
Nationality:	Ethiopian
Email:	a.degife@iggf.geo.uni-muenchen.de

Education	
2014-2020	**Ph.D.** in Geography, Faculty of Geosciences, Department of Geography, Ludwig-Maximilians-Universität München, Germany
2011-2013	**M.Sc**. in Environmental Science, Wageningen University, Netherlands
2008-2010	**M.A** in Physical Geography, Collage of Social Science, Department of Geography and Environmental studies, Addis Ababa University (AAU), Addis Ababa, Ethiopia
2002-2007	**B.A** in Geography, Collage of Social Science, Department of Geography and Environmental studies, Addis Ababa University (AAU), Addis Ababa, Ethiopia

Scientific career	
2007-2014	Lecturer at Collage of Social Science, Department of Geography and Environmental studies, Addis Ababa University (AAU), Addis Ababa, Ethiopia

Work experience	
2007-2014	Teaching B.A and M.A student, Researcher, Supervised M.A and B.A thesis and consultancy services
2009-2011	Head of Gender unit, in collage of social Sciences, Addis Ababa University

Scholarship Awards	
2014-2019	The German Academic Exchange Service (DAAD) research grants for doctoral candidates and young academics and scientists
2014-2015	The French Center for Ethiopian Studies (CFEE) research grant
2011-2013	Nuffic - The Netherlands Fellowship Programmes (NFP) Fellowships
2008-2010	The German Academic Exchange Service DAAD In Country/In-Region Scholarship

Presentations at professional conferences	
2019	Poster presentation at the annual World Bank Conference on “catalyzing innovation” in 2019.
2018	Assessment of Land Use and Land Cover Change Using GIS and Remote Sensing Techniques: A Case Study of Abobo District, Gambella Region, Ethiopia presented at the WORLD BANK Conference “Land and Poverty 2018: Land Governance in an Interconnected World” on March 19-23, 2018 Washington, DC
2017	The “Desert paradise” documentary screened and presented at the LANDac Annual International Conference 2017 “LEAVE NO ONE BEHIND: SETTING THE LAND AGENDA TO 2030”. From 29-30 June 2017 Muntgebouw, Utrecht, the Netherlands.
2017	The Intricacies of Large Scale Agricultural Investment in Gambella Region, Ethiopia presented at the WORLD BANK Conference “Land and Poverty 2017: Responsible Land Governance—Towards an Evidence-Based Approach” on March 20-24, 2017 Washington, DC 2017

LMU Graduate Center Seminars	
13-15/03/2018	Teaching Skills
06-07/12/2017	Working in International Teams - Strategies for Intercultural Collaboration
14/03/2017	Slide writing