Crop intensification options and trade-offs with the water balance in the Central Rift Valley of Ethiopia

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Nure Aleme, Girma Debas and Getnet Debas;

Liresachihu alchilim!

Abstract

The Central Rift Valley (CRV) of Ethiopia is a closed basin for which claims on land and water have strongly increased over the past decade resulting in over-exploitation of the resources. A clear symptom is the declining trend in the water level of the terminal Lake Abyata. The actual productivity of most cereals in the CRV is less than 2 t ha^{-1} associated with low input use and poor crop management. Consequently, there are two major development objectives in the CRV, i.e. producing sufficient food for the increasing population, while at the same time ensuring efficient use of limited water and land resources under variable and changing climate conditions. The low productive cereal systems and a declining resource base call for options to increase crop productivity and improve resource use efficiency in order to meet the growing demand for food.

In this thesis, the recent impacts were quantified of climate change, land use change and irrigation water abstraction on water availability of Lake Abyata of the CRV. The trends in lake levels, river discharges, basin rainfall, temperature and irrigation development (ca. 1975-2008) were analysed and the additional evapotranspiration loss resulting from temperature change and irrigated land were computed. We also analysed land use change (1990-2007) and the associated changes in runoff. Results showed that temperature has increased over 34 years ($p<0.001$) whereas annual rainfall has not changed significantly. Consequently, increased evapotranspiration consumed 62 and 145 Mm3 of additional water from lakes and land surface, respectively, during 1990-2007. Furthermore, an estimated 285 Mm^3yr^{-1} of water was abstracted for irrigation in 2009 of which approximately 170 Mm^3yr^{-1} is irrecoverable evapotranspiration loss. In addition, surface runoff has increased in the upper, and decreased in lower sub-basins of the CRV associated with extensive land use change (1990-2007).

We analysed a large number of data from farmers' fields (>10,000) and experimental data across the CRV from 2004-2009 to quantify the gaps (Yg) between actual (farm) and experimental (water-limited potential - Yw) yields of maize and wheat in homogenous farming zones. We found that the average (2004-2009) yield gap of maize and wheat ranged between 4.2-9.2 t ha^{-1}, and 2.5-4.7 t ha^{-1}, respectively, across farming zones. The actual N and P application in farmers' fields was low, as about 46% of maize and 27% of wheat fields did not receive fertilisers. We calibrated, validated and used the Agricultural Production

System Simulator (APSIM) model to explore intensification options and their trade-offs with water losses through evapotranspiration. Variety selection and N fertilization were more important for yield gap closure than crop residue management and planting density, and the magnitude of their effect depended on soil type and climate. There was a trade-off between intensification and water use through evapotranspiration, as increasing yield comes at the cost of increased transpiration. However, this trade-off can be minimized by choosing location-specific N levels at which both water use efficiency (WUE) and gross margin are maximised. These application rates varied between 75 and 250 kg N ha-1 across locations and soils, and allowed producing 80% of Yw of maize and wheat. Climate change was projected to lower Yw of maize and wheat by ca. 15-25% and 2-30%, respectively, compared to current climate conditions.

An automated gridded simulation framework was developed to scale up the promising intensification options from field scale to basin scale. We then aggregated basin scale production and identified trade-offs between production and water use for different land use scenarios. This procedure allowed designing land use scenarios based on a spatially explicit optimization of WUE and gross margin per grid cell. Consequences of land use scenarios for food production and water use at basin level were evaluated. Results of the different land use scenarios demonstrated that crop intensification options for which WUE and gross margin are maximised can meet the projected food demand (year 2050) of the growing population in the CRV while at the same time saving large areas of the currently cultivated land. In the intensification scenarios total water loss through evapotranspiration from agricultural land is reduced compared with water loss from current cultivated land and low crop productivity levels.

It is concluded that the current land use together with climate change and water abstraction for irrigation negatively affected the basin level water balance in CRV over the past decade. Furthermore, the scope for further expansion of farmland to increase food production is very limited. The focus should, therefore, be towards intensification also because the existing yield gaps are huge and hence the scope for intensification is large. Model-based exploration of intensification options can be used to prioritize promising options, to close the yield gap and for quantifying trade-offs. Scaling up of promising options allows to assess whether the food demand of the growing population can be met while at the same time saving the less productive land and water per unit agricultural product.

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Chapter 1

General introduction

1. Natural resource use and food security in the Central Rift Valley

1.1 Competition for land and water resources

The world faces increasing pressure from growing populations and economic development resulting in damage or loss of land and water resources (Garnett et al., 2013; Cassman et al., 2003; Balmford et al., 2005; Tilman et al., 2011) while climate change is expected to aggravate these problems and to impose new risks. Decreasing water resources may result in global and local conflicts and affect food production and ecosystem functioning (Vörösmarty et al., 2000; Jury and Vaux, 2007). The African Rift Valley lakes are examples of suffering from increasing claims on limited water resources (Becht and Harper, 2002; Mutiga et al., 2010a; Mutiga et al., 2010b; Hengsdijk et al., 2010).

The government of Ethiopia has formulated the Growth and Transformation Plan (GTP) as an over-arching strategic framework for development of the agricultural sector. Objectives of this plan include the sustainable increase of agricultural productivity and production, acceleration of agricultural commercialization, reduction of resource degradation and improvement of productivity of natural resources, and protection of vulnerable households from natural disasters. International donors support the GTP goals to intensify and diversify agricultural production, increase farm incomes and reduce widespread poverty. At the centre of the GTP is the need to produce more food, which may be achieved either through increasing the area of cultivated land, increasing agricultural productivity, or the combination of both. Balancing the seemingly conflicting objectives of higher food production and reducing current claims on land and water resources is a major challenge for research and development in Ethiopia.

The Central Rift Valley (CRV) of Ethiopia (approximately 1 million ha) is a closed river basin where poverty and natural resource degradation are firmly intertwined. The livelihood strategy for the majority of the population in the CRV (ca. 2 million in total) is based on small mixed rainfed farming systems comprising cereal and livestock production. Irrigated agriculture along Lake Zeway and its tributaries was introduced in the 1970s (Ayenew, 2002) and is expanding rapidly (ca. 1.9×10^4 ha in 2009), providing new income opportunities to the local population (Van Halsema et al., 2011). Irrigated agriculture is increasingly using scarce fresh water resources, which has already resulted in declining surface water resources (Alemayehu et al., 2006). Since the CRV is a closed basin, interventions in land and water resources, such as irrigation and expansion of cultivated land, have far-reaching consequences for ecosystem goods and services, and potentially undermine the sustainable use of the area and its natural resources in the future. Symptoms of resource over-exploitation are the falling water levels of lakes, particularly of Lake Abyata, declining productivity of cultivated and grazing land, and gradual erosion of wood stocks. This impairs major development objectives, such as the sustainable use of land and water resources, and feeding the growing population.

More insight is needed in the potentials and limitations of alternative land and water management practices to reduce current claims on land and water resources, and to meet the increasing demand for food. The trade-offs between potential benefits and costs of alternative crop management options, as well as the trade-offs between higher yields and associated water uses have not been quantified for the CRV. This constrains policy makers to promote appropriate land and water management practices, and donors to invest in promising options to improve the livelihoods of the local population.

1.2 The challenge of feeding a growing population

The population of Ethiopia has increased from ca. 50 million at the beginning of the 1990s to ca. 90 million in 2010 (FAO, 2013). The national population growth rate is ca 2.6% per year, while the rate is as high as 3% in some parts of the country, such as the Central Rift Valley of Ethiopia. With this rate, the population could be doubled within ca. 25 years. Feeding the growing population has always been a policy priority in Ethiopia where food insecurity induced by recurrent drought, traditional farming systems and practices, and various economic limitations has been a major problem (Veen and Tagel, 2011). For example, the wheat self-sufficiency ratio in Ethiopia has decreased from 99% in the 1960s, to 66% in the 1990s and 70 % in the 2000s (Shiferaw et al., 2011).

Overall crop production has increased over the last decades in Ethiopia, but most of the production increase was the result of an increase in agricultural land (Fig. 1). However, the rate of land expansion has stagnated in recent years because of increasing land scarcity particularly in the easily accessible areas of Ethiopia. Current productivity of most cereals is less than 2 t ha^{-1} and thus actual yields (Ya) are low. In contrast, experiments and crop simulations show that the potential yields (Yp) and the water limited yields (Yw) of cereals could be 3-4 fold larger (www.yieldgap.org; Abate et al., 2015; Kassie et al., 2014) depicting a huge yield gap (Yg). Yield gaps are defined as the difference between Yp and Ya (irrigated conditions) or Yw and Ya (rainfed conditions). Although Ya has improved in recent years (Abate et al., 2015), this is not keeping pace with the population growth, which highlights the urgency of the challenge to feed more people.

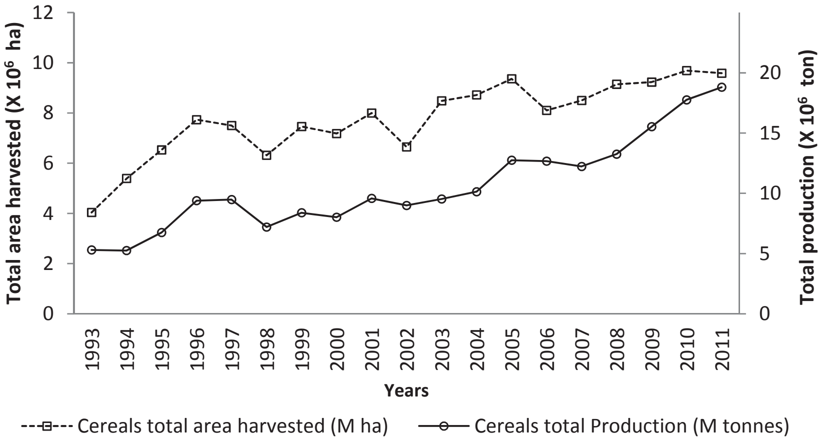

Figure 1. Trends in total cereal production and harvested area in Ethiopia. (FAO, 2013)

1.3 Climate variability and change

The East African region shows considerable temporal variation in crop yield as a result of climate variability (Thornton et al., 2009). Many parts of Ethiopia experience high interannual and intra-seasonal climate variability (Conway and Schipper, 2011; Zeleke et al., 2013). Climate variability is already imposing a significant challenge to Ethiopia by affecting food security, water supply, poverty reduction and sustainable development efforts, as well as by causing natural resource degradation and natural disasters (Bogale, 2015; Block et al., 2008). The recurrent droughts and the resulting food scarcity in Ethiopia over the past decades have been related to the variability of climate features such as onset and cessation of seasons, and dry spells within the crop growing seasons (Segele and Lamb, 2005). Also in the CRV, rainfed crop production is characterised by climate induced yield variability (Kassie et al., 2014).

In addition to the impact of climate variability, climate change poses a new risk to agriculture (Thornton et al., 2010) as it may alter crop yields through direct changes in temperature and water availability. Indirectly, Ya and Yg may be affected through changes in pest and disease infections as a result of climate change (Rosenzweig et al., 2001). Average crop yields across Sub-Saharan Africa (SSA) are projected to fall by ca. 20% by 2050 due to climate change (Ringler et al., 2010; Porter, 2014). Climate projections for Ethiopia show continued warming trends, which will result in faster crop development, reducing the time to reach crop maturity, and hence lower crop biomass and yield. Higher CO_2 levels are expected to partly counteract these negative effects in C3 plants such as wheat. Warmer temperatures may also increase water loss through soil evaporation and transpiration, which could reduce crop water availability and reduce yields. This effect may be profound in Ethiopia, and in the CRV in particular where food crops are predominantly grown under rain fed conditions.

Climate projections for Ethiopia show less agreement with respect to rainfall (Conway and Schipper, 2011). Consequently, there are differences in reported impacts of climate change on crop yield, depending on location, climate models and types of climate variables considered. For example, climate change is generally projected to reduce crop yields in Ethiopia (Arndt et al., 2011; Mideksa, 2010) and in the CRV (Kassie et al., 2015) mainly due to higher temperatures. In contrast, Muluneh et al. (2014) reported a possible increase in rainfall and hence increased yields in the CRV, though their approach did not put much emphasis on the most obvious change, i.e. that of temperature. Some studies also suggest that yield increases may be expected with climate change in the cooler highlands of Ethiopia (Admassu et al., 2013).

1.4 Implications of intensification of agriculture

Garnett et al. (2013) presented four premises underlying sustainable intensification: (i) the need to increase production; (ii) increased production must be met through higher yields because increasing the agricultural area carries major environmental costs; (iii) food security requires as much attention as increasing environmental sustainability; and (iv) sustainable intensification denotes a goal but does not specify a priori how it should be attained or which agricultural techniques to deploy.

The need to increase production in the CRV has been described in Section 1.2. As agricultural land is becoming scarce, particularly in highly populated areas of Ethiopia, this will have to be achieved through increasing productivity instead of expansion of agricultural land (Byerlee et al., 2014; Tilman et al., 2002). In sustainable intensification, environmental sustainability requires as much attention as food security (Garnett et al., 2013).

To increase productivity, the merits and adverse effects of diverse approaches should be rigorously tested and assessed. Accurate, spatially explicit knowledge about yield gaps is essential to guide sustainable intensification of agriculture (Van Ittersum et al., 2013). Furthermore, different intensification options are associated with specific amounts of water and nutrient inputs and primary outputs that result in location-specific resource use efficiencies. Understanding this complexity requires the combination of a large number of genetic, environmental and management factors, which are difficult to integrate through experimentation. Therefore, a model-based analysis of the spatially explicit yield gaps, and the exploration of a large set of management options and intensification scenarios can inform stakeholders and decision makers as to how to ensure food production while at the same time mitigating further expansion of cultivated land, and improving resource use efficiency.

Increasing crop productivity may require more water per unit of area compared with low productivity levels. However, the overall amount of water transpired to produce a targeted production in a basin could be less if the targeted production could be attained from less land. Understanding the effects of changes in crop management should, therefore, include the analysis of associated changes in water use at different spatial scales.

2. Objectives of the thesis

The overall objective of this study is to identify and quantify crop intensification options under variable and changing climate conditions at field and river basin level in the Central Rift Valley of Ethiopia. Main focus is on the two major development objectives in the CRV i.e. producing sufficient food for the increasing population, while at the same time ensuring efficient use of limited water and land resources under variable and changing climate conditions. The analysis combines empirical data and crop growth simulation at field scale and basin scale. The specific objectives are:

1. To quantify the historical impacts of climate change, land use change and irrigation water abstraction on the CRV water system (Chapter 2).
2. To analyse the current productivity, resource use efficiency and yield gaps of maize and wheat production across different farming zones in the CRV (Chapter 3).
3. To explore sustainable crop intensification options at field level to narrow the yield gap and analyse trade-offs with the water balance (Chapter 4).
4. To scale up the promising crop intensification options that increased productivity at maximum WUE and gross margin. Scaling up was done from field level to basin level with water use and food production calculated and mapped for several scenarios of targeted food production (Chapter 5).

3. Case study area

The study was conducted in the Central Rift Valley (CRV) of Ethiopia (38°00'-39°30' E and 7°00'-8°30' N), which covers about one million ha and is part of the Great African Rift Valley. The study area is in the centre of the Ethiopian Rift, 150 km southwest of Addis Ababa, and encompasses a network of rivers and three large lakes, i.e. Lake Zeway, Abyata and Langano, and three major rivers, Bulbula, Meki and Ketar. The CRV is a closed river basin with elevations ranging from 1600 m above sea level (a.s.l.) in the valley floor to about 3500 m a.s.l. in the east and west.

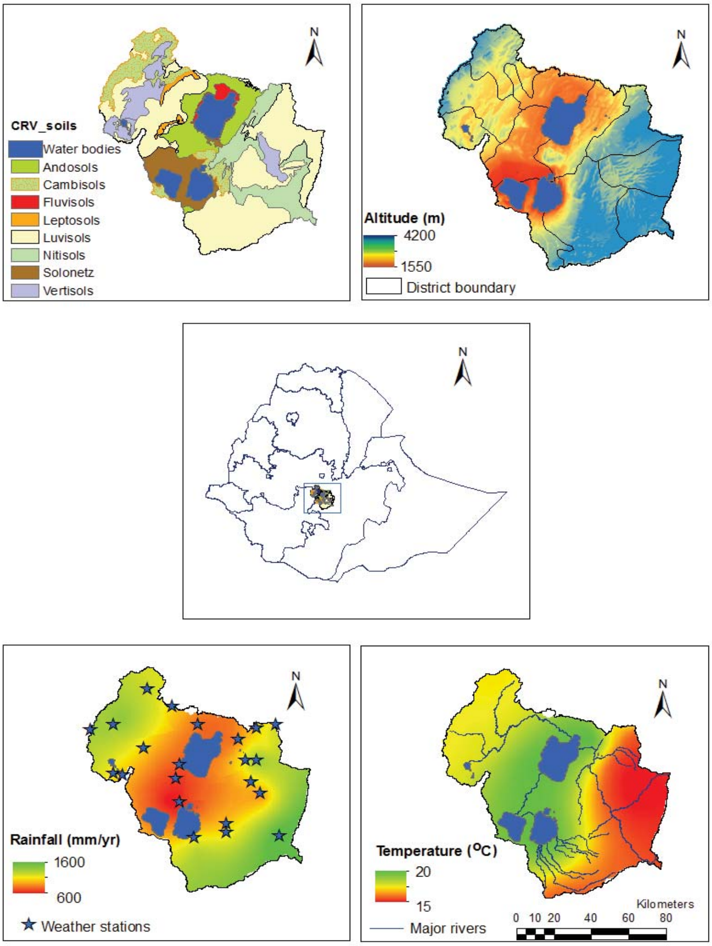

Figure 2. Maps of the Central Rift Valley of Ethiopia including information on major soils, altitude, annual rainfall and average temperature.

Annual rainfall in CRV ranges from about 600 mm near the lakes in the valley floor up to 1600 mm at higher elevations near the borders of the basin (Fig. 2). About 70% of the rainfall precipitates in the short rainy season (July to September). Average annual temperature varies from 19 °C in the valley floor to about 14 °C at higher elevations (Fritzsche et al., 2007).

The soils in the western part of the CRV are mainly Cambisols and Luvisols in the hills and foot slopes with Vertisols in parts of the plains (Fig. 2). Around Lake Zeway, soils are Vertic Andosols and Fluvisols associated with the delta. In the eastern part, towards the Arsi plateau, Luvisols dominate but with appreciable areas of Nitosols and some areas with Vertisols.

4. Methodology

Sustainable use of land and water resources and feeding the increasing population are two major development objectives in the CRV. Using empirical methods, this thesis diagnosed the major problems including the decline of water resources and low crop productivity. The diagnosis provided an entry point to explore future sustainable intensification options at field scale, and scale up the most promising ones to design new land use scenarios at basin scale using crop simulation models (Figure 3).

In order to understand how the water system in the CRV (particularly the level of the terminal Lake Abyata) is affected, the thesis focussed on the three major developments in CRV i.e. climate change, land use change and the increasing water abstraction for irrigation. The trends in historical climate records (>30 years) of rainfall, temperature and the associated evapotranspiration, as well as lake levels and river discharges were analysed for the CRV.

The productivity, resource use efficiencies and yield gaps of maize and wheat systems were analysed by combining empirical data and methods at field and basin scale. One of the main challenges in this type of analysis was availability of the required data because conducting dedicated farm surveys and experiments for at least 5 years, which is necessary for robust yield gap and resource use analysis (Van Ittersum et al., 2013), and covering a large number of fields that represent the entire CRV, is very difficult. The approach followed in this thesis to overcome these problems was to evaluate and use two sets of data that have never been used for this type of analysis: (1) the agricultural sample surveys annually collected by the central statistics authority (CSA) from a large number of fields of households; (2) experimental yield data from a number of research locations owned by the Ethiopian Institute of Agricultural Research that were originally designed for National Variety Trials (NVTs).

Climate and soil conditions are key drivers for differences in potential yield across a region (Tittonell and Giller, 2013; Lobell et al., 2009). The first step towards reducing yield gaps (Yg) is to obtain realistic estimates of their magnitude and their spatial and temporal variability (Hochman et al., 2013). Therefore, the study area is classified into so-called homogeneous farming zones and multiple years of yield data are used. Subsequently, various intensification options for these farming zones have been explored using a crop simulation model, and a large number of variety, environment and crop management combinations have been tested to select promising ones.

Agronomic experiments are conducted at particular points in time and space, making results site- and season-specific. Because experiments are time consuming and expensive (Jones et al., 2003) it is difficult to cover a large number of soils, climate conditions, crop management options and years. Crop simulation models can assist in capturing the interactions among genetic, environmental and management factors by integrating data and knowledge on soil, water, crop and climate (Whisler et al., 1986). Crop models have many potential uses such as adding value to field experimentation and demonstration, and identification of systems constraints and opportunities. They can also generate information or enhance system understanding for policy makers and farmers (Whitbread et al., 2010).

Crop simulation models have, for example, been used to simulate water and nitrogen dynamics (Probert et al., 1998), deep drainage and N leaching (Stewart et al., 2006), crop growth and yield formation processes (Asseng et al., 1998), and yield response to different management options (Moeller et al., 2007; Mupangwa and Jewitt, 2011; Peake et al., 2008) and climate (Jones et al., 2003; Keating et al., 2003; Holzworth et al., 2014). We calibrated and used a detailed crop simulation model to explore promising crop intensification options from many combinations of genetic, environment and crop management options at field scale. In selecting promising intensification options, water use efficiency (WUE; defined here as kg of grain yield per mm of water lost by evapotranspiration per year), and gross margins were used as indicators instead of looking at maximum yield only (Pretty et al., 2011).

The biophysical conditions that determine crop production, such as rainfall, temperature and soil characteristics, vary in the CRV and, therefore, the potential for intensification is location-specific. Hence, analysis of crop production and the water balance at basin scale for the CRV using spatially explicit soil, climate and crop management information can give a unique opportunity to estimate basin level aggregated production and water use.

While cropping system models provide detailed simulation capabilities at field level, their application to the basin level requires a creative setup. A gridded based crop growth simulation approach was developed using spatially explicit soil hydrologic properties including the soil's available water capacity and effective root zone depth using the recently completed GYGA-AfSIS dataset (http://www.isric.org/data/afsis-gyga-functional-soil-information-sub-saharan-africa-rz-pawhc-ssa-version-01-0; Leenaars et al., 2015) and climate data. Per grid cell crop yields and associated water balances were simulated. Based on plausible food demand scenarios, future land use scenarios mitigating expansion of cultivated land and avoiding unnecessary water use at the basin level were explored.

5. Outline of the thesis

This thesis comprises four complimentary research chapters that combine empirical and simulation methods at field and basin scale (Fig. 3). Chapter 2 quantifies the effects of climate change (basin rainfall, temperature and evapotranspiration), land use change (with the resulting runoff change) and water abstraction for irrigation on the CRV water system. Based on one of the findings from Chapter 2, i.e. that expansion of cultivated land to marginal areas provides little scope for increasing crop production, Chapter 3 analyses the yield gaps of wheat and maize, and resource uses across homogeneous farming zones in the CRV and presents the prospects for increasing productivity through intensification. Chapter 4 presents a model-based exploration of field scale intensification options that are promising to narrow the prevailing yield gaps in the CRV under current and future (2050s) climate conditions. In Chapter 5, basin scale intensification options that are found to be efficient in terms of water use efficiency and gross margin are presented using the options identified in Chapter 4. Basin scale land use scenarios are presented based on current and targeted food production, water use efficiency and gross margin. The discussion and conclusions of the thesis in Chapter 6 present the linkage between the various chapters, methodological strengths and limitations, and outlooks on future research and experimentation.

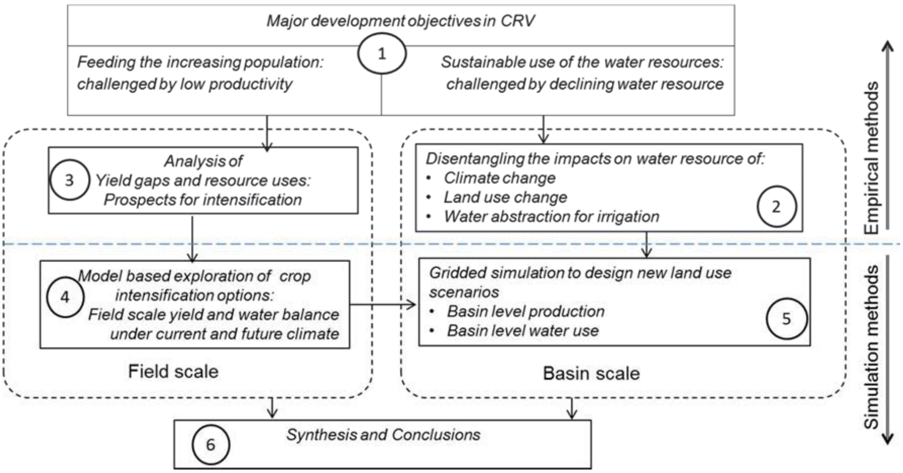

Figure 3. Structure of the research and thesis (numbers refer to Chapters)

Chapter 2

Disentangling the impacts of climate change, land use change and irrigation on the Central Rift Valley water system of Ethiopia

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Abstract

The Central Rift Valley (CRV) of Ethiopia is a closed basin where claims on land and water have strongly increased over the past decade resulting in over-exploitation of the resources: a clear symptom is the declining trend in the water level of the terminal Lake Abyata. In this paper, we quantify the plausible recent impacts of climate change, land use change and irrigation water abstraction on water availability of Lake Abyata. We examined trends in lake levels, river discharges, basin rainfall, temperature and irrigation development (ca. 1975-2008), and computed the additional evapotranspiration loss resulting from temperature change and irrigated land. We also analysed land use change (1990-2007) and estimated the subsequent change in surface runoff. Temperature has increased linearly over 34 years ($p<0.001$) whereas rainfall has not changed significantly. Consequently, increased evapotranspiration consumed 62 and 145 Mm^3 of additional water from lakes and land surface, respectively, during 1990-2007. Furthermore, an estimated 285 Mm^3yr^{-1} of water was abstracted for irrigation in 2009 of which approximately 170 Mm^3yr^{-1} is irrecoverable evapotranspiration loss. In addition, surface runoff has increased in the upper, and decreased in lower sub-basins of the CRV associated with extensive land use change (1990-2007). However, insight in the impact of the net increase in runoff of 260 Mm^3 yr^{-1} on the water availability for Lake Abyata remains partial because of data and methodological limitations. We conclude that the potential for agricultural intensification and its hydrological implications should be considered jointly to prevent further deteriorating Lake Abyata.

Keywords: Curve Number method, evapotranspiration, lake levels, river discharge, agriculture, intensification

1. Introduction

The East African Rift Valley, stretching from the Afar region in Ethiopia to Mozambique in Southern Africa, faces increasing pressure from growing populations and increasing economic development (e.g. (Becht and Harper, 2002; Hengsdijk et al., 2010; Mutiga et al., 2010). The Rift Valley comprises some of the largest inland lakes of the world such as Lake Malawi and Lake Tanganyika. Many of the lakes in the East African Rift Valley have no outlet to sea, making them very sensitive to developments that affect the local hydrology and water quality (UNEP, 2004). Recent awareness of the potential impacts of climate change and major land use change on the East African Rift Valley Lakes and its population has increased concerns that current developments are unsustainable (Bezabih et al., 2011; Mango et al., 2011; Verburg et al., 2003; Zeray et al., 2007).

One of the basins in the East African Rift Valley that shows a rapid transformation is the Central Rift Valley (CRV) in Ethiopia. Claims on land and water resources have strongly increased in the CRV over the past decade due to various developments. Most obvious effect of these developments is the falling water level of Lake Abyata, which is part of the Lake Shala-Abyata National Park and forms the terminal lake of the closed CRV basin (Legesse and Ayenew, 2006). The size of this lake has been reduced by more than 50% between 1973 and 2006 (Hengsdijk et al., 2009).

The predominant livelihood strategy for the majority of the population (about 2 million) in the CRV is the small mixed rain fed farming system comprising cereals (wheat, barley, maize and teff) and livestock. As a consequence of a growing population the cropping area more than doubled at the expense of forests and grassland between 1973 and 2006 (Garedew et al., 2009). Land use change may affect the local hydrology through its impact on evapotranspiration differences among vegetation types, runoff and infiltration. More recently and associated to favourable government policies aimed at reducing poverty through agricultural intensification, the area for irrigated horticulture and floriculture has rapidly increased. Recent investments in irrigated agriculture have stimulated economic growth and development but claim their share of the limited water resources in the CRV (Van Halsema et al., 2011). Others argue that recent changes in climate, particularly decreased rainfall has contributed to changes in the hydrology and the falling water level of Lake Abyata (Ayenew, 2002; Meshesha et al., 2010).

Since the CRV is a closed basin, i.e. there is no inflow and outflow of surface water, relatively small interventions affecting the water system can have great consequences for the terminal Lake Abyata and potentially undermine the sustainable use of the basin resources (Ayenew, 2004, 2007; Legesse and Ayenew, 2006). However, quantitative insight is lacking on the potential contribution of various developments, i.e. land use change, increased irrigation and climate change, on the drying up of Lake Abyata. Therefore, the question here is whether we can disentangle the possible effects of these different developments and processes on the water system of the CRV, which may support the identification of appropriate measures and policies to halt the decline of Lake Abyata.

The objective of this paper is to quantify the possible impacts of climate change, land use change and increased irrigation on the water system of the CRV, and specifically Lake Abyata. First, we analysed historical climate records of rainfall and temperature and the associated evapotranspiration and the possible impact on the water system of the CRV. Second, land use change for two reference years was analysed as well as the associated change in runoff across various land units in CRV. Third, the increase of the irrigated area is quantified on the basis of which we estimated the associated fresh water abstraction. In combination with a quantitative analysis of the changes in lake levels and river discharges over the past 30 years we attempt to better understand to what extent the three developments have affected Lake Abyata. Special efforts were made to also show the inherent inaccuracies and uncertainties of these quantitative results.

2. Description of Central Rift Valley

The CRV is a closed basin within the Rift Valley Lakes Basin (RVLB), which is one of the eleven major river basins in Ethiopia (Fig. 1a). The CRV (approximately between 38°81′ and 39°8′ E, and 7°10′ to 8°30′ N) measures about 1.03 10^4 km^2 and comprises a chain of three major lakes (i.e. Lake Zeway, Abyata and Langano) with unique hydrological and ecological characteristics (Abebe and Geheb, 2003).

Climate in the CRV varies markedly with altitude. The annual average daily temperature of about 16°C in the eastern and western highlands (3000 m a.s.l.) increases to 21°C in the central lowlands (1600 m a.s.l.). Rainfall shows an opposite spatial trend and varies from 600 mm in the central lowlands to about 1600 mm yr^{-1} in the highlands. About 70% of the rainfall precipitates in the main rainy season from June to September, while a short rainy season is from March to May.

The CRV has diverse soil types with different infiltration and associated runoff potential. Coarse textured soils with high infiltration rates are dominant in the eastern and western highlands and in the valley floor around the lakes. Medium textured soils with moderate infiltration rates dominate the eastern and western mid altitudes of CRV whereas the foothills of western highlands and some places in central part of eastern CRV are dominated by fine textured black soils (Vertisols) with lower infiltration capacity.

The CRV consists of a network of rivers and lakes and can be divided into seven connected sub-basins, i.e. Meki, Ketar, Zeway, Bulbula, Langano, Horakelo and Abyata (Fig. 1a). The Meki and Ketar sub-basins drain to Lake Zeway through the Meki (a) and Ketar (b) rivers, respectively (Fig. 1b). Lake Zeway also collects surface runoff from the Zeway sub-basin. Lake Zeway has natural overflow through the Bulbula River (c) to Lake Abyata. Several small seasonal streams feed Lake Langano from the south-eastern plateau, while the lake drains to Lake Abyata seasonally via the Horakelo River (d). The Bulbula and Horakelo rivers, in addition to connecting Lake Abyata to Lakes Zeway and Langano, respectively, collect direct runoff from their respective sub-basins.

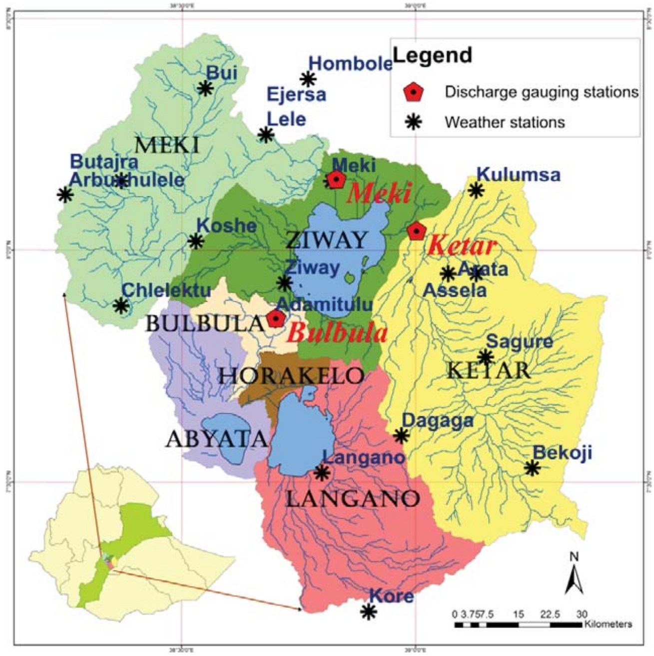

Figure 1a. Map of the Central Rift Valley which consists of seven sub-basins (shown in different colours), i.e. Meki, Ketar, Zeway, Bulbula, Horakelo, Abyata and Langano. Further, 17 weather stations (black font) are shown, as well as three discharge gauging stations (red font) used in the study.

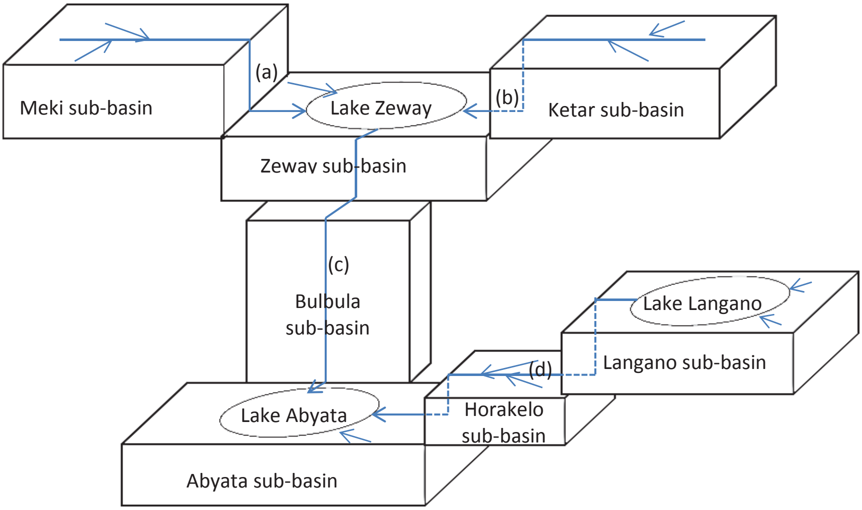

Figure 1b. Schematic representation of the seven sub-basins in the Central Rift Valley and their inter-connectivity. Letters (a), (b), (c) and (d) represent the Meki, Ketar, Bulbula and Horakelo Rivers, respectively.

Recently, water abstraction for irrigation has increased considerably in a small part of central valley of the CRV. Because the water of both Lake Langano and Lake Abyata has high salinity levels, irrigation development in the CRV is confined to the Zeway sub-basin along Lake Zeway and between the discharge gauging stations of the Meki, Ketar and Bulbula Rivers (Fig. 1a).

3. Materials and Method

3.1 Conceptual approach

In our approach the water system of the CRV is characterised by the water levels of Lake Zeway, Abyata and Langano and the discharge levels of three gauged rivers (Ketar, Meki and Bulbula; Fig. 2). Since the CRV is a closed basin, lake levels and river discharges reflect the variation in annual perception under unchanged conditions. The outflow of water from the CRV system through groundwater from Lake Abyata is negligible (Ayenew, 2004). Climate change, land use change and water abstraction (for irrigation) may affect system characteristics albeit through different processes.

We considered rainfall and temperature trends as proxies for the manifestation of climate change, which both may affect the water system of the CRV. First, changes in rainfall may affect the CRV water system as rainfall is the only water input to the system. An increase in total basin rainfall increases the amount of water that is available downstream if other water outputs are kept constant: river discharges and lake levels will follow the rainfall trend. Second, increased temperature will affect the water system through increased evapotranspiration losses of the prevailing land use and increased evaporation losses from water bodies in the CRV. To quantify the possible impact of climate change on the CRV water system we analyse historical rainfall and temperature records of the CRV and we estimate reference evapotranspiration (ETo) for the period 1975- 2008. As ETo is an estimate of the evaporative demand of the atmosphere where water is sufficiently available, we use it as a proxy to estimate water loss from water bodies and further utilize crop coefficients to estimate vegetation evapotranspiration from the terrestrial surface in the CRV.

Land use affects the basin water system through its effect on evapotranspiration, runoff and infiltration differences among land use types. In this analysis, we use 1990 and 2007 land use data, first to identify and quantify changes in land use. Second, we use these land use data to quantify the change in associated runoff during this period.

Upstream abstraction of water directly affects water availability in downstream Lake Abyata such as for irrigated agriculture. To estimate the amount of consumptive water use associated with irrigated agriculture we analyse the development of the irrigated area in the CRV between 2002 and 2009.

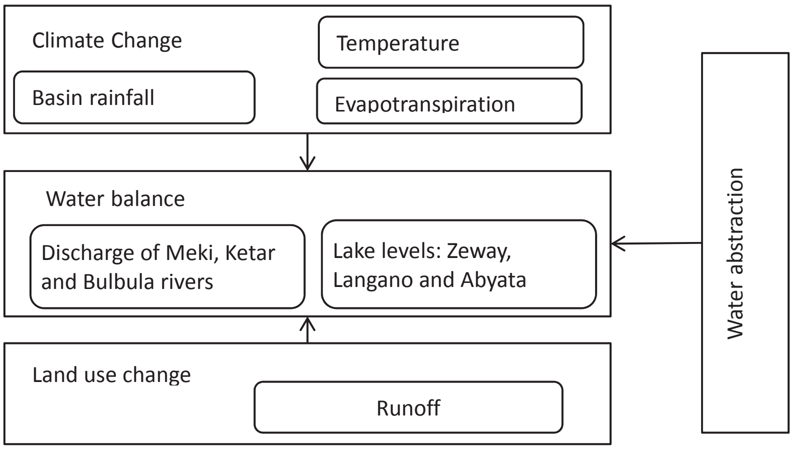

Figure 2. Conceptual approach followed to quantify the effect of climate change, land use change and water abstraction on sustainable water availability of the Central Rift Valley basin. The direction of the arrow indicates cause-effect relationships.

3.2 Data sources

Spatial and attribute data were obtained from various sources and formats (Table 1), which have been projected using Transverse Mercator projection parameter that is suitable for the CRV (Chekol, 2006). Map projections are attempts to render the three dimensional surface of the earth on to a planar surface; they are designed to minimize distortions while preserving the accuracy of the image elements including shape, area, distance, and direction.

Table 1. Description of the data types, sources, reference period, scale/resolution and purposes of various databases used in the study.

Data base	Data format	Source*	Reference period	Scale/ resolution	Used to:
Rainfall	Table	NMA & EIAR	1975-2009	Daily	Analyse rainfall trends
Temperature	Table	NMA & EIAR	1975-2009	Daily	Analyse temperature trend and compute evapotranspiration
River discharge	Table	MoWR	1975-2008	Daily	Analyse trends in river discharges
Lake level	Table	MoWR	1975-2009	Daily	Analyse trends in lake level
Soil	Vector	MoWR	2007	1:250,000	Determine Hydrological Soil Groups
Land use	Vector	MoA	1990	1:250,000	Model land use and runoff changes
Land use	Vector	MoWR	2007	1:250,000	Model land use and runoff changes
Weather stations	Vector	NMA	2009	17 stations	Construct Thiesson polygons

* MoWR=Ministry of Water Resource; NMA= National Meteorological Agency; MoA= Ministry of Agriculture; EIAR=Ethiopian Institute of Agricultural Research

Meteorological data were obtained from the National Meteorological Agency of Ethiopia. A spatial climate database was developed consisting of daily rainfall records of 17 weather stations across the CRV (Fig. 1a). Similarly, a database was developed with daily temperature records of three representative stations, i.e. Assela, Butajira and Zeway, across the CRV covering a period of more than 30 years (Table 2).

Time series of daily discharge data of gauged rivers Ketar and Meki (1975-2005), and Bulbula (1980-2005) as well as lake level data of Zeway, Langano and Abyata were obtained from the Ministry of Water Resources (MoWR). Lake levels were measured from a local reference point for each lake. Hence, absolute lake water levels cannot be compared among the three lakes.

Land use maps of 1990 and 2007 were used for analysis of land use change. Land use in the year 1990 was based on Landsat Thematic Mapper (TM) images of 1986 to 1989 (MoA, 2004), while land use in the year 2007 was based on a Landsat Enhanced Thematic Mapper (ETM) of 2001 that was updated with Aster image of 2005/2006 and on ground truth verification in 2007 (MoWR, 2007). A digital soil map of the CRV (1:250,000), comprising information on soil types, drainage, depth and texture classes was extracted from the Rift Valley Lakes Basin (RVLB) master plan database (MoWR, 2007), and was used to define hydrologic soil groups (Section 3.5).

Bureaus of agriculture at district level provided information on the development of the irrigated area during the period 2002-2009 in the Zeway sub-basin.

3.3 Lake levels and river discharges

Time series data of observed annual minimum, maximum and mean daily levels of the Lakes Zeway, Langano and Abyata, and the total annual discharge of Meki, Ketar and Bulbula Rivers were analysed using linear regression.

3.4 Climate change

Seventeen weather stations were selected out of more than 25 stations within and in the proximity of the CRV, taking into account their spatial distribution and availability of at least 30 years of rainfall data (Table 2).

Table 2. Metadata of the weather data in the Central Rift Valley.

Station	Altitude	Data period	Years with missing values
Adami Tulu	1655	1966 - 2008	1971-1974
Arata	1836	1974 - 2008	
Assela *	2410	1966 - 2008	2008
Bekoji	2786	1974 - 2008	2006-2008
Bulbula	1602	1968 - 2008	
Butajira *	2102	1969 - 2008	
Chelelektu	1840	1973 - 2008	
Ejersalale	1817	1967 - 2008	1973
Hombole	1761	1968 - 2005	1993-1996
Kore	2732	1966 - 2008	2006
Koshe	1842	1975 - 2008	
Kulumsa	2082	1969 - 2008	1984
Langano	1623	1970 - 2008	
Meki	1665	1967 – 2008	2008
Ogolcho	1749	1974 - 2008	1979-1980, 2008
Sagure	2527	1973 - 2008	2000
Zeway *	1648	1970 - 2008	

* Weather stations for which temperature (minimum and maximum) trend analysis has been conducted.

Based on the 17 weather stations, Thiessen polygon method (Thiessen, 1911) was used to convert point rainfall data into spatial distribution of rainfall data (e.g. Cabus, 2008; Fortes et al., 2005; Jang et al., 2007). Missing rainfall data were filled by values from the nearest station. Daily rainfall data were aggregated to annual rainfall volume values.

The CRV was divided into seven sub-basins using a Digital Elevation Model (DEM). The total volume of rainfall received each year (1975 to 2008) in each sub-basin, and in the entire CRV was then calculated as:

$$BRF_k = \sum_{j=1}^{n} \sum_{i=1}^{m} A_{ij} RF_{ijk} \qquad \text{eq. 1}$$

In which:

BRF_k= total rainfall volume in CRV for year k (m^3),

A_{ij}= area of the i^{th} polygon in the j^{th} sub-basin (m^2),

RF_{ijk}= total rainfall in the i^{th} polygon of the j^{th} sub-basin for year k (m),

n = number of sub-basins in CRV (n= 7),

m = number of Thiesen polygons in j^{th} sub-basin.

In addition to changes in total basin rainfall, changes in sub-basin rainfall of Meki, Ketar and Bulbula for the period of 34 years (1975-2008) were analysed using a linear regression, and the relationship between sub-basin rainfall and sub-basin discharges.

Observed average annual minimum, maximum and mean temperature data (1975 to 2008) from Assela, Zeway and Butajira weather stations were used to study the temporal trend in temperature in the eastern highlands, central lowland and western highlands, respectively. A linear trend analysis was conducted for the minimum temperature (Tmin), maximum temperature (Tmax) and mean temperature (Tmean) of the three weather stations. We conducted a t-test to test whether the slope of the regression line differed significantly from zero. The change in Tmin and Tmax between 1975 and 2008 was estimated based on the linear trend of Tmin and Tmax (Fig. 7a and 7b).

Reference evapotranspiration was calculated using the FAO Penman-Monteith equation as described in Allen et al. (1998) using CROPWAT 8.0 and based on monthly, minimum temperature, maximum temperature, and mean wind speed, relative humidity and sunshine hours. We used observed historical monthly averages of Tmin and Tmax to calculate time series ET_0 for the period of 1975 to 2008. Because complete long-term records (>30 years) of relative humidity, wind speed and sunshine hours from weather stations in the CRV were lacking, we used monthly averages of the period 1989-1993 of these parameters from Assela, Zeway and Butajira for the ET_0 calculations. We analysed the linear trend in ET_0 using a t-test while we attributed the change in ET_0 to the change in temperature only. The additional water loss due to the increased Tmax and /or Tmin is then estimated for Lake Zeway, Langano and Abyata. Because the used Penman-Monteith equation (Allen et al., 1998) assumes that water is abundantly available at the reference evapotranspiring surface, and also because the lakes in the study area are deep enough to prevent excessive surface heating, it is assumed that ET_0 approximates the evaporation loss from these free water bodies. The change in evapotranspiration loss from land surface in CRV was estimated considering the crop coefficient (Kc) and stress factor (Ks) values for various vegetation types (FAO, 1998) and taking into account the land use change between 1990 and 2007. The different land use types in CRV were identified and the area of each land use type was calculated for both years using ArcGIS. Crop coefficient (Kc) values were assigned for each land use type based on the type of vegetation. The evapotranspiration from different land use types was then calculated by multiplying the ET_0 with Kc of the respective land use type of both 1990 and 2007. The difference in evapotranspiration between the two years was calculated, weighted by the area of each land use type, as the amount of additional water lost from terrestrial land due to climate change and land use change.

3.5 Land use change and runoff

The Natural Resource Conservation Service (NRCS)-Curve Number (CN) method (USDA-NRCS, 2004) was used to estimate the effect of land use change on the surface runoff of sub-basins between 1990 and 2007. The CN method has been developed specifically for drainage basins where no runoff has been measured. It estimates the direct runoff given an index (=curve numbers) describing runoff response characteristics based on land cover, land use management and soil characteristics.

The amount of runoff is quantified by the following equations:

$$Q_i = \frac{(R_i - I_a)^2}{(R_i - I_a) + S} \quad \text{if } R_i > I_a \qquad \text{eq. 2}$$

$$Q_i = 0 \quad \text{if } R_i \leq I_a \qquad \text{eq. 3}$$

$$Q_{ann} = \sum_{i=1}^{366} Q_i \qquad \text{eq. 4}$$

Where:
Q_i = the daily runoff (mm),
Q_{ann} = annual runoff depth in a specific area (mm),
R_i = the rainfall depth for the i^{th} day of the year (mm),
S = the maximum retention parameter,
I_a = the initial abstraction which is assumed to be 0.2 S.

Retention parameter (S) is defined by equation:

$$S = \frac{25400}{CN} - 254 \qquad \text{eq.5}$$

So-called Hydrological Soil Groups (HSG) were identified for the CRV based on spatial distribution of soil characteristics in the CRV including infiltration capacity, texture, depth and drainage conditions (USDA-NRCS, 2004). These HSG were over-layed with the prevailing land use types in 1990 and 2007. Corresponding CNs were derived from the National Engineering Handbook (USDA-NRCS, 2004) and from research results in Ethiopia (Descheemaeker et al., 2008) and assigned to polygons.

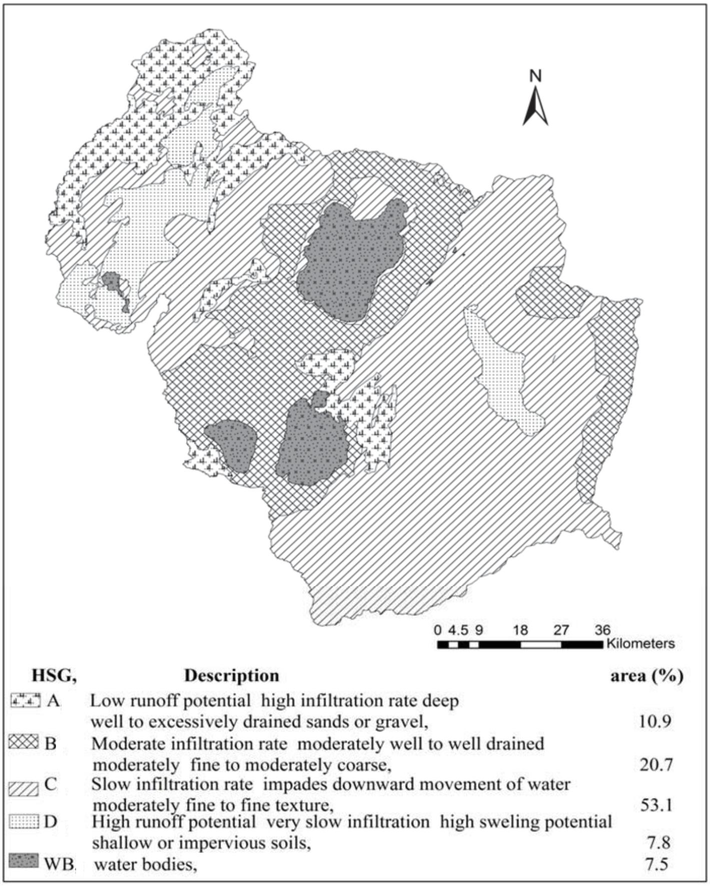

Figure 3. Hydrological Soil Groups (HSG), their descriptions and the percentage of the spatial coverage of soils under various Hydrological Soil Groups in the Central Rift Valley.

Subsequently, surface runoff was computed for the days with rainfall (R_i) greater than initial abstraction ($I\alpha$) (eq. 2), and zero runoff was assigned otherwise (eq. 3). This was done for all land units resulting from the combination of Thiessen polygons, hydrologic soil groups and land use types based on land use data of the two reference years. The difference in runoff between both reference years was analysed to quantitatively assess the impact of land use change on surface runoff. A map showing the areas with an increase, no change and decrease in runoff between the two reference years was produced to indicate the spatial impact of land use change.

3.6 Water abstraction for irrigation

We estimated water abstraction for irrigation based on the area expansion of irrigated agriculture between 2002 and 2009 in two CRV districts where irrigated agriculture is concentrated. In the irrigated lands of the CRV, approximately two crops per year are grown. One cropping cycle is in the dry season and completely depends on irrigation water. In the other cropping cycle, however, irrigation is only supplementary because a good part of the cycle is in the main rainy season. Based on informal discussions with farmers, experts and researchers, we estimated that ca. 50% of the water that is applied in the fully irrigated crop is used for supplementary irrigation in the second cycle. Hence, we assumed that "1.5 irrigated crops" per year are cultivated with an average application rate of 10,000 m^3 ha^{-1} per cropping season and a water use efficiency of 35% based on empirical results from the CRV (Van Halsema et al., 2011).

4. Results

4.1 Trends in river discharges and lake levels

Although there are significant relationships between the annual discharges of the three gauged rivers (Meki, Ketar and Bulbula) and annual rainfall (data not shown), there are no significant trends in the annual discharge of these rivers because of the high standard errors of estimates of annual discharge (Fig. 4). While the coefficient of variation (CV) of the annual basin rainfall from the Meki, Ketar and Bulbula sub-basins is ca. 15%, the CVs of annual discharge from Meki, Ketar and Bulbula rivers are 40, 29 and 64%, respectively. This suggests that the other water balance components and perhaps also measurement errors affected the discharges in the rivers. We continue with presenting average annual discharges over the period 1975-2004 for Meki, 1975-2005 for Ketar and 1980-2005 for Bulbula.

The Ketar sub-basin is the largest (31% of the CRV area) of the seven sub-basins in CRV and its main outlet, the Ketar River yields the highest average annual discharge (406 $Mm^3\ yr^{-1}$). The Ketar sub-basin also has the highest discharge/rainfall ratio (14%) followed by the Meki sub-basin (12%) and the Bulbula (2%) sub-basin. The high discharge/rainfall ratio may be related to a higher drainage density of the Ketar sub-basin compared to other sub-basins. The higher elevation gradient of the Ketar sub-basin may result in a rapid surface drainage in the form of direct runoff from individual rainfall events before major evaporation losses occur. The Meki River discharges 271 $Mm^3\ yr^{-1}$, while the Bulbula River discharges on average the lowest volume (167 $Mm^3\ yr^{-1}$).

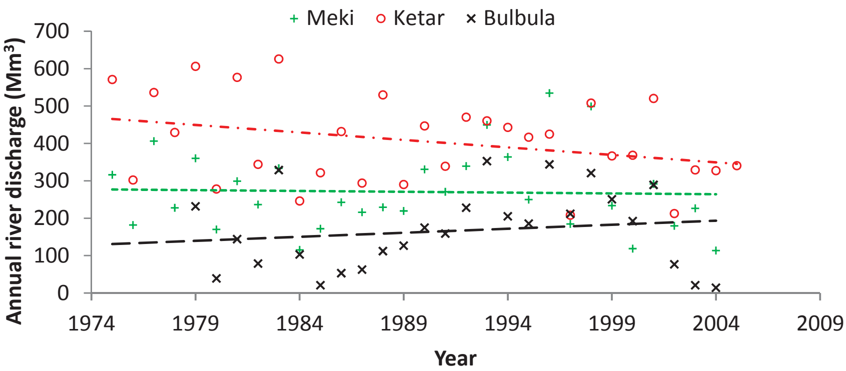

Figure 4. Trends in discharge of the Meki, Ketar and Bulbula rivers. All trend lines are not significantly deviating from a horizontal line.

Figure 5 shows the annual minimum, maximum and mean lake levels of Zeway, Langano and Abyata. While the lake levels of Zeway and Langano do not show a significant change ($p>0.05$) since 1975, the lake level of Abyata has decreased dramatically ($r^2 = 0.66$; $p<0.001$) at an average rate of about 0.165 m yr^{-1}. Lake levels of Zeway and Langano are quite resilient as both lakes function according to an overflow principle: if the inflow of water in both lakes exceeds their capacity more water will flow out through the Bulbula and Horakelo rivers, respectively. This can be observed from the robust relationship between monthly Zeway lake levels and rainfall in dry, normal and wet years (Annex I). Similarly, when Lake Zeway and Langano receive less water (e.g. through feeder rivers) less water will flow out of the lakes. In the latter case, minimum water levels will drop at the end of the dry season but these will recover at the end of the rainy season (Annex I).

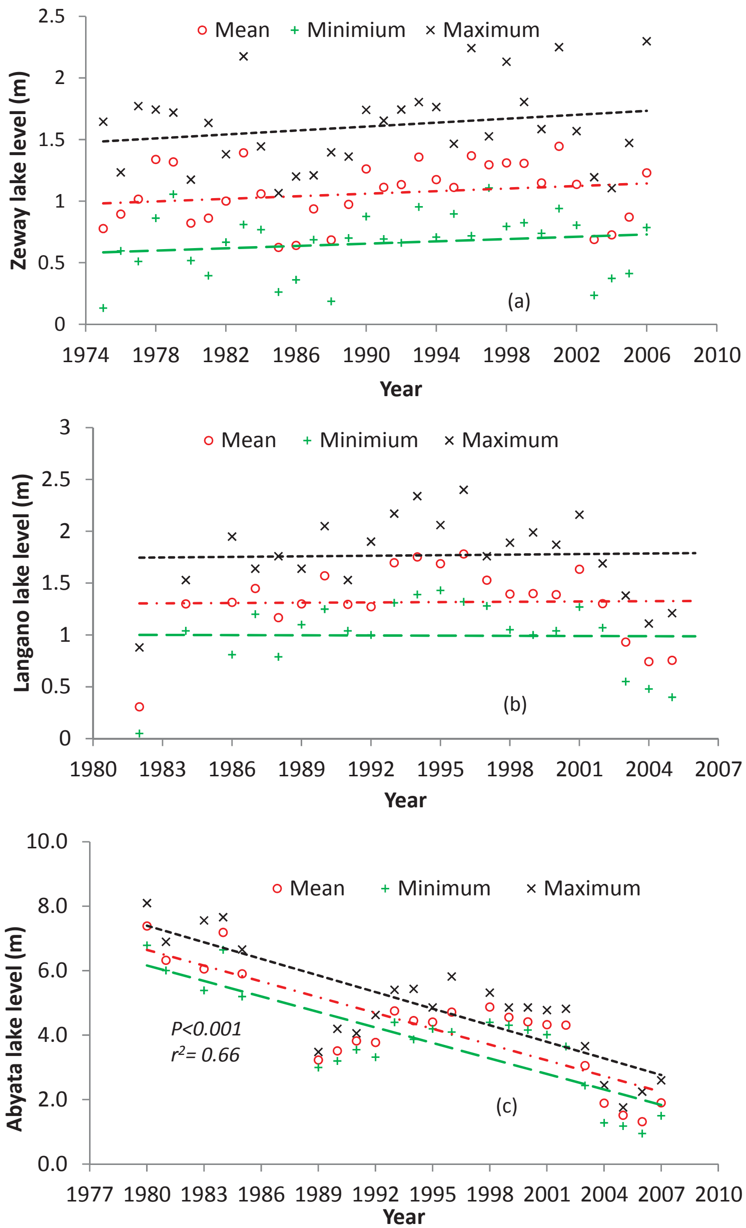

Figure 5. Trend of annual minimum, mean and maximum lake levels (m) of Zeway (a) Langano (b) and Abyata (c). Trends for Zeway and Langano are not significant.

4.2 Climate change: rainfall, temperature and evapotranspiration

The annual volume of basin rainfall in the CRV has not changed between 1975 and 2008, and is approximately 9.3 10^9 m^3. In addition, the three gauged sub-basins Ketar, Meki and Bulbula do not show a significant change in annual rainfall in this period (Fig. 6).

In addition to the total annual rainfall also the distribution of rainfall over the main rainy season (June - September) and the short rainy season (March - May) as well as the number of rainy days per year did not change significantly across weather stations in the CRV during the period of 1975 to 2008 (data not shown).

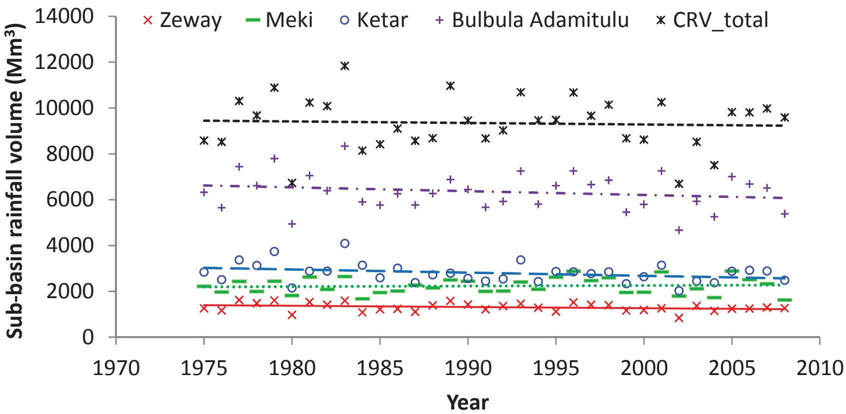

Figure 6. Trends in annual rainfall volumes in the gauged sub-basins Meki, Ketar and Bulbula. All trends are non-significant.

In contrast to rainfall, significant temperature changes have been observed in the eastern highlands (Assela), central lowlands (Zeway), and western highlands (Butajira) over the period 1975-2008. The daily minimum temperature (T_{min}) increased significantly at Assela ($p<0.001$; Fig. 7a), and daily maximum temperature (T_{max}) increased significantly ($p<0.001$) in all the three weather stations (Fig. 7b). Mean temperature (T_{mean}) increased significantly both in Zeway and Assela ($p<0.001$; Fig. 7c).

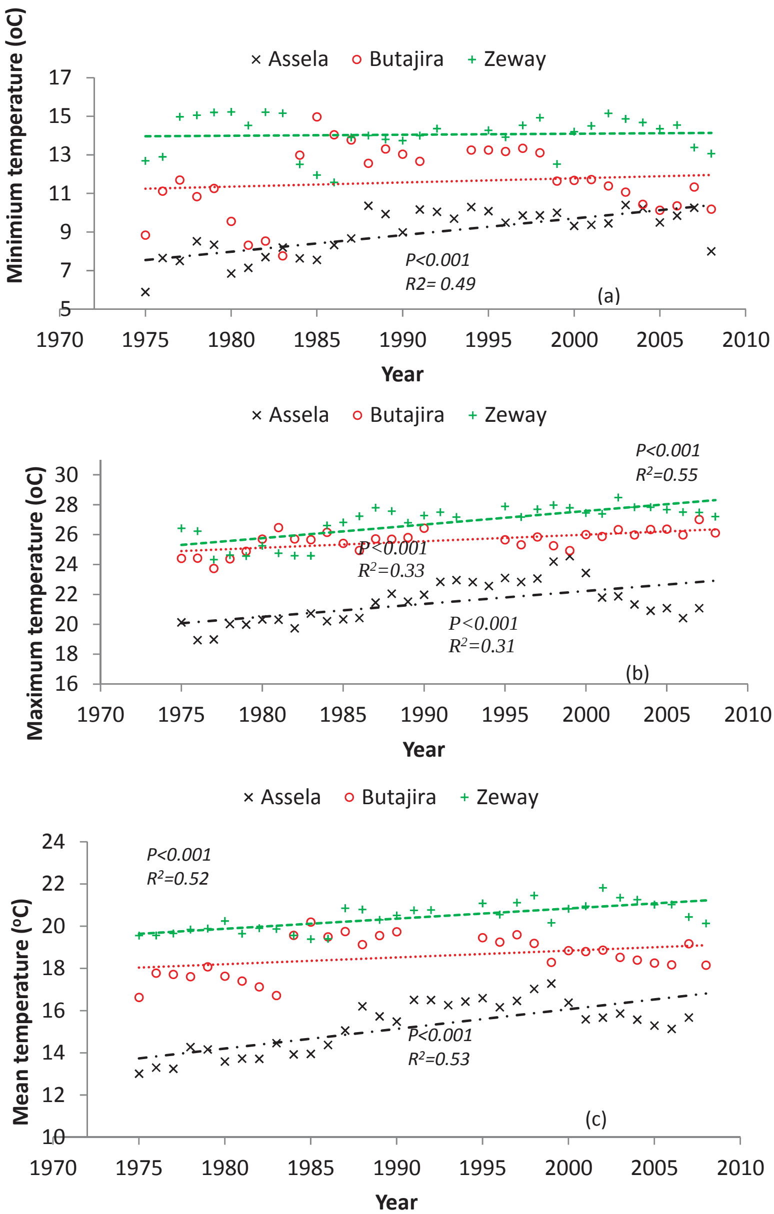

Figure 7. Temporal trends in minimum (a), maximum(b) and mean(c) temperature in the eastern highlands (Assela station); central lowland (Zeway station); and western highlands (Butajira station) of the Central Rift Valley of Ethiopia. Significant trends are indicated.

Associated with changes in temperature ETo is affected differentially across the CRV. Because of the temperature changes ETo has increased by 0.55, 0.45 and 0.21 mm day^{-1} at Assela, Zeway and Butajira, respectively in the period 1975-2008 (Fig. 8). The increase in ETo is significant in all the three locations ($p<0.001$ for Assela and Zeway, and $p=0.01$ for Butajira), whereas the change is highest at Assela because both Tmin and Tmax increased most in this location. The temperature increase in Butajira was lowest which is reflected in the relatively small increase in ETo. The estimated daily ETo in 2008, while assuming other weather factors constant (Section 3.4), suggests an increase with 14% in Assela, 10% in Zeway and less than 5% in Butajira compared to the situation in 1975.

Based on the Zeway climate data and assuming unchanged lake areas between 1975 and 2008, higher temperatures have increased evaporation losses from Lake Zeway, Langano and Abyata with about 67 Mm^3, 37 Mm^3 and 14 Mm^3, respectively. For the period in which land use change was analysed (1990-2007; Section 4.3), we calculated ETo with the regression equation. Consequently, we found that ca. 62 Mm^3 more water has been lost from the three lakes in this period. Similarly, taking into account the temperature and land use changes between 1990 and 2007; actual evapotranspiration loss from terrestrial land in CRV has increased by 145 Mm^3. Thus, the total increase in evaporative losses from both water bodies and land surface between 1990 and 2007 is estimated at 207 Mm^3.

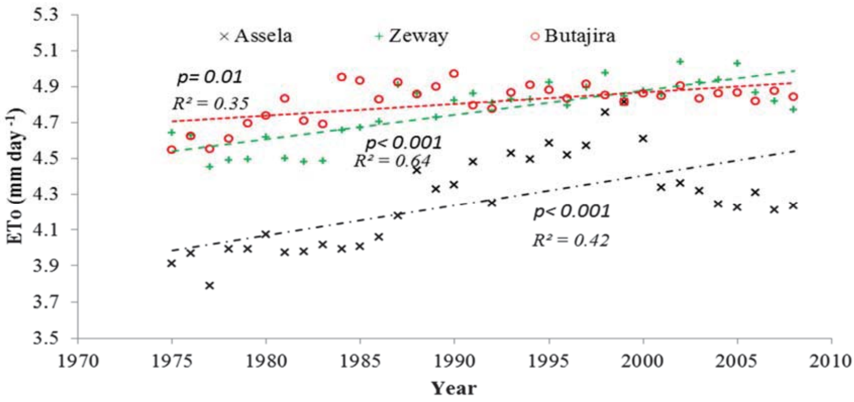

Figure 8. Change in ETo between 1975 and 2008 at Assela, Zeway and Butajira as a consequence of changes in monthly minimum and maximum temperatures in this period.

4.3 Land use change and consequence for surface runoff

Table 3 shows the change in land use in the CRV between 1990 and 2007. The largest decrease occurred in the land use types ‘bush-shrub-grassland’ and ‘moderately cultivated land’, while especially the land use type ‘intensively cultivated’ increased. In 2007 almost 50% of the land in the CRV was classified as ‘intensively cultivated’ underlining the agricultural intensification since 1990. The total cultivated area in the CRV has increased between 1990 and 2007 with more than 10%. Some land use types have completely disappeared since 1990: wooded grassland, bush-shrub-grassland and dense woodland (Table 3; Fig. 9).

Table 3. Land use change between 1990 and 2007 in the Central Rift Valley of Ethiopia.

Land use type	1990		2007		Land use change	
	Area (km^2)	% of total	Area (km^2)	% of total	Area (km^2)	% of CRV
Afro alpine	455.3	4.4	415.3	4.0	-40.0	-0.4
Exposed surface	211.7	2.1	144.7	1.4	-67.0	-0.7
Disturbed mixed high forest	128.4	1.2	417.4	4.1	289.0	2.8
Plantation forest	0.0	0.0	36.0	0.4	36.0	0.4
Open grassland	181.0	1.8	114.1	1.1	-67.0	-0.7
Wooded grassland	310.3	3.0	0.0	0.0	-310.3	-3.0
Dense Shrub land	243.3	2.4	116.7	1.1	-126.6	-1.2
Open shrub land	200.1	1.9	431.1	4.2	231.0	2.2
Bush-Shrub-Grassland	903.0	8.8	0.0	0.0	-903.0	-8.8
Marshland	45.4	0.4	160.7	1.6	115.3	1.1
Open woodland	405.3	3.9	220.6	2.1	-184.7	-1.8
Dense woodland	57.8	0.6	0.0	0.0	-57.8	-0.6
Built up	278.1	2.7	278.1	2.7	0.0	0.0
Intensively cultivated	3164.8	30.8	5130.8	49.9	1966.0	19.1
Moderately cultivated	2850.1	27.7	2031.2	19.8	-818.9	-8.0
Water bodies	839.7	8.2	777.4	7.6	-62.3	-0.6
CRV total	10274.2	100	10274.2	100		

Negative values indicate a decrease in size/ percentage of land use types in 2007 compared to 1990 whereas positive values indicate an increase. Intensively cultivated land is a land unit where 80% or more of the mapping unit is cultivated whereas moderately cultivated land is where less than 80% of the area is cultivated (MoWR, 2007).

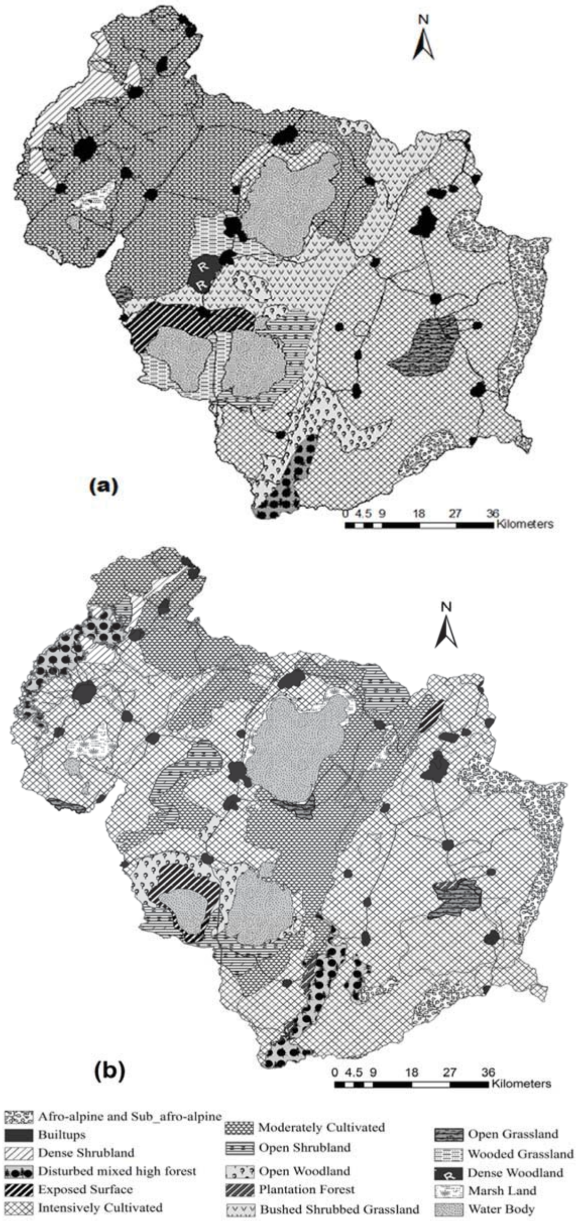

Figure 9. Land use maps of the Central Rift Valley for the years (a) 1990 and (b) 2007 respectively.

Associated with the change in land use between 1990 and 2007, surface runoff changed in 50% of the land area of the CRV. About 35% of the land area showed an increase in surface runoff, while 15% of the land area a decrease (Table 4; Fig. 10). Land use change resulted in an overall increase of surface runoff of 260 Mm^3 across the CRV (Table 4). However, changes in runoff differed greatly across the various sub-basins of the CRV. The Zeway and especially the Meki sub-basins showed the largest increase in runoff associated with major conversions of moderately cultivated land and bush-shrub-grassland into intensively cultivated land between 1990 and 2007 (Fig. 9). In contrast, the smaller Horakelo and Abyata sub-basins showed a considerable decrease in run-off during the same period (Table 4).

Table 4. Change in runoff volume between 1990 and 2007 and the proportion of land area with an increase, no change and decrease of runoff in seven sub-basins of Central Rift Valley of Ethiopia.

Sub-basin	Surface runoff change between 1990 and 2007								Runoff change (Mm^3)*
	Increase			No change		Decrease			
	Area (km^2)	% of area	Runoff volume (Mm^3)	Area (km^2)	% of area	Area (km^2)	% of area	Runoff volume (Mm^3)	
Abyata	330.7	47.7	33.9	166.9	24.1	195.1	28.2	-68.1	-34.2
Bulbula	261.1	80.4	19.0	50.2	15.5	13.5	4.2	-4.6	14.3
Horakelo	83.3	47.9	2.1	28.1	16.2	62.5	35.9	-21.1	-19.0
Ketar	526.9	16.0	38.5	2353.1	71.3	422.3	12.8	-8.4	28.4
Langano	351.8	18.6	31.9	824.9	43.7	712.9	37.7	-32.0	-0.8
Meki	1160.0	52.1	182.6	946.8	42.6	117.9	5.3	-7.4	175.1
Zeway	888.3	51.6	98.1	787.7	45.7	45.8	2.7	-2.2	95.9
CRV	3602.0	34.9	406.1	5157.8	49.9	1570.1	15.2	-143.7	259.7

* Runoff change is computed as the runoff estimated based on 2007 land use minus runoff from that of 1990. Negative values suggest a decrease in runoff and vice versa.

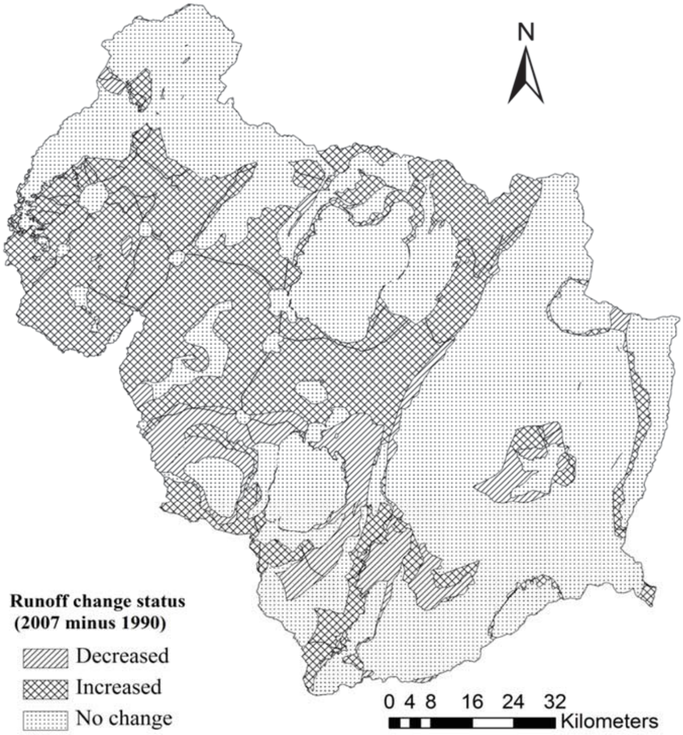

Figure 10. Difference in direct runoff between 2007 and 1990 across the Central Rift Valley.

4.4 Trends in irrigation development and total water abstraction

Based on the expansion of the irrigated area in the CRV, estimation of the amount of water abstracted for irrigation is as follows: Irrigated agriculture has increased from 1,435 ha in 2002 to 16,510 ha in 2009 in two districts, west and north of Lake Zeway (Fig. 11). Consequently, claims on freshwater for irrigation in these two districts has increased from approximately 22 to 248 Mm^3yr^{-1}. Although time series data is lacking another 2,580 ha of land is currently being irrigated in a third district east of Lake Zeway. Adding the water abstraction for this irrigated area totals about 285 Mm^3yr^{-1} of fresh water that is currently abstracted for irrigation.

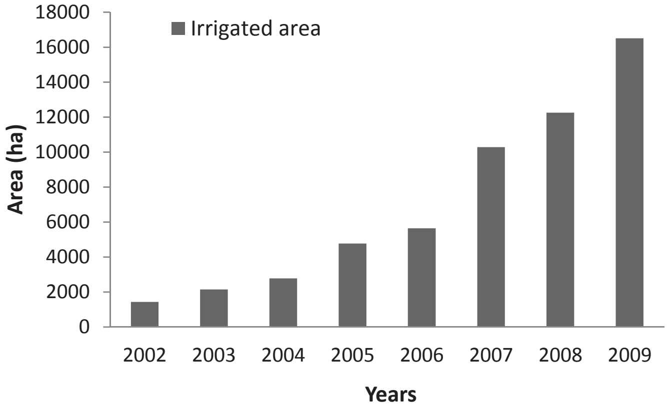

Figure 11. Temporal trend of the irrigated area in the two Districts (Dugda and Adami Tulu Judo Kombolcha) in the Central Rift Valley between 2002 and 2009.

5. Discussion and conclusions

5.1 Limitations of data and methods

The limitations in the data and methods employed in this study may have implications for our results. The data available for various analyses cover different periods, e.g. for land use change the period 1990-2007, climate change the period 1975-2008, and irrigation development the period 2002-2009. This complicates disentangling the effects of the three developments, i.e. land use change, climate change and irrigation expansion, may have had on the water system and more specifically Lake Abyata. While major irrigation development has taken place after 2002 (Fig. 11) lake level and discharge data are only available till 2005 leaving little basis to analyse the potential impact of irrigation expansion on lake levels and discharge data. Moreover, the quality of the available discharge data is low showing high standard errors. Therefore, the potential impact of very recent irrigation development on the CRV water system remains largely hidden.

The NRCS-CN method has limitations with respect to the aggregation of all the three abstractions of any single storm event (rainfall interception, depression storage, and infiltration) into one term, the Initial abstraction (Ia), that hampers the relative partitioning of rainfall into individual components. The most important limitation, however, is that the NRCS-CN method does not take into account the spatial interaction of runoff among polygons (USDA-NRCS, 2004). It also assumes uniform antecedent moisture distribution for each rainfall event (White et al., 2011). In practice, however, polygons are spatially connected and their moisture status may not be uniform. Hence, runoff from one polygon may provide moisture to the soil of adjacent polygons (if the next lower polygon is drier) instead of adding to the runoff of adjacent polygons. This makes it difficult to quantify the impact on lake Abyata with a great accuracy as more sophisticated methods that are integrated with other flow routing models are difficult to apply because of data requirements (Baltas and Karaliolidou, 2007; Mello et al., 2008). Therefore, results of the CN based analysis should be interpreted with care and merely suggest that land use change in a relatively short period has had a considerable effect on surface runoff patterns in the CRV.

5.2 Effects of climate change, land use change and irrigation

Our analysis provides quantitative insight in the system changes over the past decades in CRV with respect to climate, land use and irrigation development that affected water availability in the terminal Lake Abyata. Climate change has affected the basin water balance over the past decades mainly through its effect on increased evapotranspiration associated with significantly higher temperatures. Consequently, about 207 Mm^3 of additional water is lost through evaporation (from lakes) and evapotranspiration (from land surface) in 2007 compared to 1990. This is approximately half of the lake evaporation and evapotranspiration changes experienced during 1975-2007 assuming a linear increase in temperature and ETo over this period. This is an irrecoverable loss and much larger than the average annual water volume that Lake Abyata receives through the Bulbula River.

Land use has changed in CRV between 1990 and 2007 in the form of expansion of cultivated land and increase in the intensity of cultivation. Consequently, runoff has generally increased in the CRV, although there are places where runoff has decreased. The major increase comes from Meki, Zeway and Ketar sub-basins that feed Lake Zeway whereas the decrease in runoff is observed in the Abyata and Horakelo sub-basins that directly feed the terminal Lake Abyata. As rainfall did not change significantly between 1990 and 2007, the increase in runoff is not a net addition to the CRV hydrology; and most likely went at the expense of infiltration. More detailed studies are needed to quantify this shift between water balance components.

Irrigated land is expanding rapidly putting more pressure on fresh water resources. About 19,000 ha were irrigated in 2009 for which an estimated 285 Mm^3yr^{-1} of fresh water is abstracted. More important is that all abstracted water may not be completely lost from the CRV water system. Assuming 35% consumptive water use efficiency (used by evapotranspiration), and 25% evaporation losses from the conveyance system and drainage runoff, about 170 Mm^3 of the abstracted water is irrecoverably lost to the atmosphere whereas the remaining portion remains within the water system of the CRV. This suggests that irrigation has resulted in considerable productive water losses, especially in recent years, at the expense of the water flow to Lake Abyata.

In conclusion, the water level of Lake Abyata is far more clearly affected by the combined effect of climate change, land use change and irrigation water abstraction than Lake Zeway and Lake Langano. This is explained by the fact that the lake levels of Zeway and Langano are resilient as they are regulated through the 'over-flow' principle (Section 4.1; Annex I), i.e. less inflow of water into these lakes or increased water abstraction from these lakes is compensated by a lower outflow from these lakes. In contrast, Lake Abyata is a terminal lake that completely depends on surface rainfall, the supply through its feeding rivers Horakelo and Bulbula and the runoff from its sub-basin. Rainfall has not changed in the recent past (section 4.2), but the water supply from its feeding rivers has decreased due to higher ETo losses at Lake Zeway and Langano (Section 4.2) and the abstraction of irrigation water near Lake Zeway (Section 4.4). At the same time, also the runoff to Lake Abyata decreased due to land use changes in Abyata sub-basin (Table 4), and ETo has increased due to increased temperature since 1975 (Section 4.2).

5.3 Concluding comments

Temperature has significantly and linearly increased in the CRV over 34 years (1975-2008) leading to an increase in evapotranspiration whereas rainfall has not changed significantly. Increased evapotranspiration consumed 62 and 145 Mm^3 of additional water from lakes and land surface, respectively, during the period for which land use changes have been recorded, i.e., 1990-2007. Furthermore, in 2009 an estimated 285 Mm^3yr^{-1} of water was abstracted for irrigation of which approximately 170 Mm^3yr^{-1} is irrecoverable evapotranspiration loss. In addition, surface runoff has increased in the upper, and decreased in lower sub-basins of the CRV associated with extensive land use change between 1990 and 2007.

More detailed analyses are possible when better quality and more complete data are available. It is important to improve the monitoring the CRV water system considering the fall in Lake Abyata and the water availability of downstream water users in general. Therefore, stakeholders operating in CRV need to have a shared vision and subsequent actions to realize a high quality and continuous hydro-meteorological monitoring system and database.

Future use of resources must take into account that land use change, temperature increase and increase in water abstraction all affect the water systems of the CRV. Climate change and water abstraction for irrigation have induced extra evapotranspiration loss. The water use efficiency of irrigated farms should be improved in order to reduce the amount of water abstracted in the CRV and increase water availability in Lake Abyata and/or to accommodate future irrigation expansion without the need to abstract additional water.

Therefore, future agricultural production system need to focus on exploring production levels that are efficient in water use and provide sustainable supplies of water to downstream lakes.

The present high share of cultivated land suggests limited scope for the further expansion of cultivated land. Hence the potential for agricultural intensification and its hydrological implications at various scales should be explored in order to ensure sufficient food production and sustainable availability of water downstream. Although the impact of land use change on the surface runoff pattern is well understood, the insight in the quantitative impact on Lake Abyata is still partial. Future studies need to consider the use of physically based basin models to better understand the hydrological consequence of various land use scenarios.

Acknowledgements

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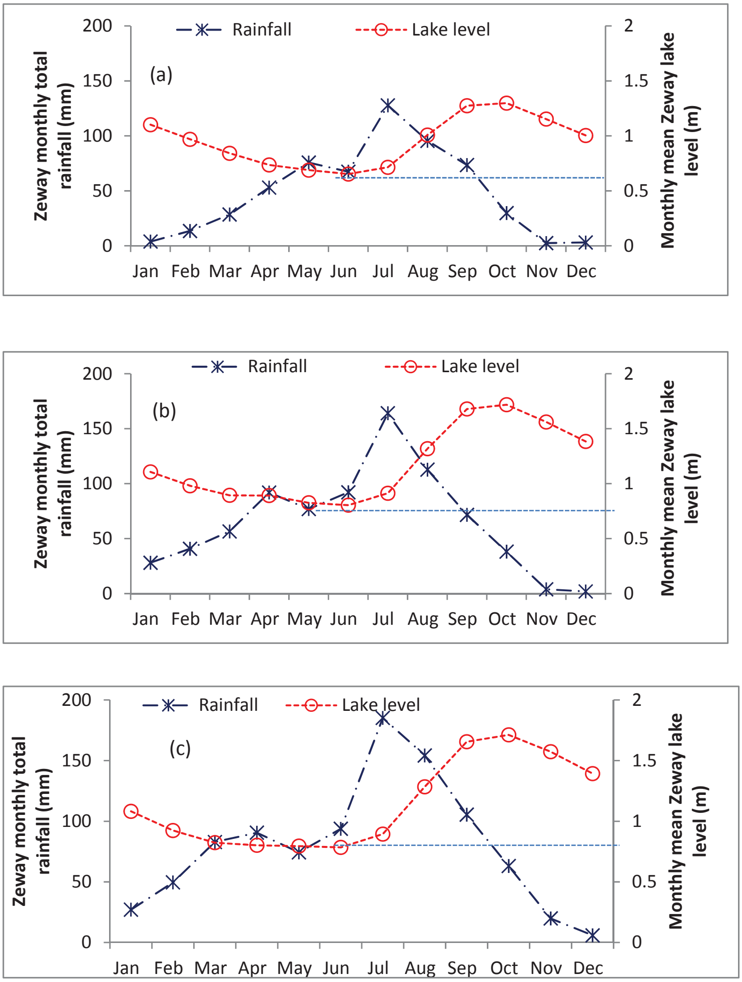
Annex I



Relationships between monthly rainfall at Zeway and the monthly mean level of Lake Zeway showing variation of lake level in response to the rainfall in dry (a), normal (b) and wet (c) years with average annual rainfall of 575 mm 779 mm and 952 mm respectively. Rainfall data (1975-2008) was classified into lower, middle, and upper one-third ("tercile") to represent dry, normal and wet years, respectively. Although rainfall differs considerably among the dry, wet and normal years, the minimum lake level is only slightly affected despite differences in maximum lake levels.

Chapter 3

Yield gaps and resource use across farming zones in the Central Rift Valley of Ethiopia

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Abstract

In the Central Rift Valley (CRV) of Ethiopia low productive cereal systems and a declining resource base call for options to increase crop productivity and improve resource use efficiency in order to meet the growing demand for food. We compiled and analysed a large number of data from farmers' fields (>10,000) and experimental data across the CRV from 2004-2009 to quantify the gaps (Yg) between actual (average and best performing farmers) and experimental (water-limited potential - Yw) yields of maize and wheat in homogenous farming zones. Resource use efficiencies (nutrients, water) of maize and wheat were also analysed to assess the spatial variation and scope for improvements. The average (2004-2009) yield gap of maize and wheat in CRV ranged between 4.2-9.2 t ha^{-1}, and 2.5-4.7 t ha^{-1}, respectively, across farming zones. The Yg was lowest in the Central lowlands where Yw was also lowest, i.e. 6.5 t ha^{-1} for maize and 4.4 t ha^{-1} for wheat, compared with Yw in the Eastern highlands (11 t ha^{-1} for maize and 6.7 t ha^{-1} for wheat) and Western highlands (10.8 t ha^{-1} for maize and 5.7 t ha^{-1} for wheat). The actual N and P application in farmers' fields was low, as about 46% of maize and 27% of wheat fields did not receive fertilisers, while the average applied mineral fertiliser rates across all farmers (2.6-16.5 kg N ha^{-1} and 2.2-17.3 kg P ha^{-1} across HFZs and crops) were far below the recommended rate. On average, best performing farmers applied 8-20 kg N ha^{-1} and 5-21 kg P ha^{-1} ranging across HFZs and crops. Increasing N application to recommended rates had only a small effect on narrowing the yield gap under current farmers' management. Therefore, yield gap closure strongly depends on improving other aspects of crop management, while paying attention to the interaction with nutrient management. Since rain water use efficiency (seasonal rainfall) of water-limited yields was 12-17.3 kg mm^{-1} for maize and 7.4-10.6 kg mm^{-1} for wheat and much higher than that of actual yields (2.7-4.3 kg mm^{-1} for maize and 2.3-3.5 kg mm^{-1} for wheat), improving the input use and crop management can increase water use efficiency. The large set of experimental and survey data enabled us to gain insight in the spatial and temporal variation in yield gaps and input rates and in differences between average and best performing farmers.

Key words: Intensification, production ecology, actual yield, water limited yield,
resource use efficiency, maize, wheat, central rift valley

1. Introduction

The increasing demand for food globally (Godfray et al., 2010; Ray et al., 2013) is particularly pertinent in developing countries where the population as well as the per capita food consumption is growing much faster than in developed countries (Kearney, 2010). An evident example is Ethiopia whose population has increased from about 53.5 million in 1994 to 74 million in 2007 (CSA, 2007) and it is projected to reach about 180 million by 2050 (Admassu et al., 2013). So far, the increase in food production to feed the growing population has been mainly achieved through expansion of cultivated land (Abate and Lemenih, 2014; Dessie and Kleman, 2007; Tsegaye et al., 2010). For example, the area of maize and wheat cultivation in Ethiopia has increased by 3.1 10^4 ha yr^{-1} and 5 10^4 ha yr^{-1}, respectively, between 1993 and 2012 (FAO, 2013). Fertile land for agricultural expansion is becoming scarce (Garedew et al., 2009; Gebrelibanos and Assen, 2013; Zeleke and Hurni, 2001), but productivity growth in Ethiopia is low and the national average yield of most cereals is well below 2 t ha^{-1} (FAO, 2013). A declining resource base (Ali et al., 2011), degraded soils (Meshesha et al., 2012), erratic climatic conditions (Ayenew, 2002; Kassie et al., 2014a) and nutrient depleted soils (Haileslassie et al., 2005) are severely constraining the cereal yields in rainfed systems. Due to financial and market access problems, current fertiliser and other input use across the country is low and the adoption of yield-increasing production technologies by farmers is limited (Spielman et al., 2011).

The Central Rift Valley (CRV) of Ethiopia is a typical example of such on-going processes. Grazing land has been gradually converted into cropland and currently, there is little scope for the further expansion of the crop area (Getnet et al., 2014). Hence, the focus should be on increasing productivity and on improving resource use efficiency based on a better understanding of the climate and biophysical resource base, as well as the socio-economic-institutional context in which local farming systems operate.

Quantitative understanding of the temporal and spatial variation in actual and potential crop productivity is lacking and information on the difference between the two (the so-called yield gap) is only partially available for part of the CRV, and based on limited actual yield data (Kassie et al., 2014b). However, there is a large amount of yield data that is regularly collected from farmers' fields for all major crops to estimate annual production. In addition, there is experimental data collected from federal and regional research stations as part of crop improvement programs. Until now, these databases have not been used beyond their original purpose, i.e. to improve the quantitative understanding of yield gaps across crops and locations.

The physical environment affects the inputs required to realize a particular production level (Van Ittersum and Rabbinge, 1997). Resource use efficiencies (RUE) are, therefore, highly variable as a result of soil variability and weather conditions, but also farmers' management decisions affect crop responses to applied nutrients (Tittonell et al., 2005). Moreover, yield-reducing factors, such as pest, disease and weed infestation can result in strong reductions in use-efficiency of resources (Giller et al., 2006).The lack of information on resource use efficiencies and the scope for their improvement hampers the identification of strategies for the development of alternative/improved land use systems. RUE is important from an economic and environmental point of view (De Wit, 1992). Understanding the resource use and RUE of current production systems helps to identify possibilities for producing more with the available resources and to understand variations across farming zones and years.

The objective of this paper is to quantify the gaps between actual (farmers' average) and experimental (water-limited potential) yield levels of maize and wheat in different farming zones of the CRV. We bring together and analyse a large number of data from farmers' fields (> 10,000 unique observations) and experimental data, and use these empirical data for (yield gap) calculation. We quantify yield gaps of both average and the top 5% farmers (hereafter 'best performing farmers') and we seek relationships across years between yield gaps on the one hand and rainfall and nutrient application rates on the other hand. Moreover, we analyse the resource use efficiencies (nutrient, water) of maize and wheat in different farming zones to assess the spatial variation in RUE and scope for improvements. Finally, we discuss the performance of current maize and wheat systems and the theoretical potential for intensification.

2. Materials and methods

2.1 Description of the study area

The Central Rift Valley (CRV) basin is situated at the border of two regional states of Ethiopia, Oromia and Southern Nations, Nationalities and Peoples (SNNP). A total of 11 districts (corresponds with *Weredas*) are part of the CRV basin (between 38°81´ and 39°8´ E, and 7°10´ to 8°30´ N) (Fig. 1).

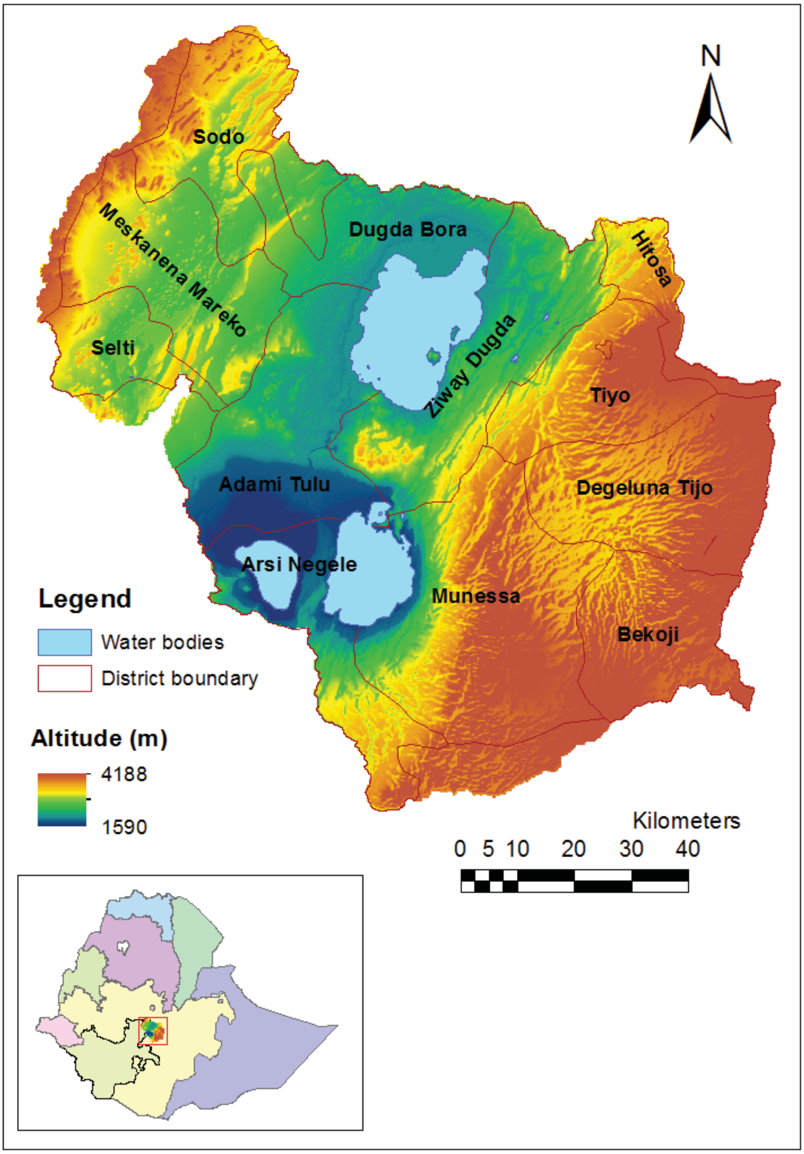

Figure 1. Location map of the Central Rift Valley of Ethiopia.

Rainfall increases from approximately 600 mm yr^{-1} at the bottom of the Central lowlands to about 1600 mm yr^{-1} in high altitudes of the Eastern and Western highlands following an altitude gradient. The bimodal rainfall distribution is characterised by a short rainy season (*Belg*) in March and April and a long rainy season (*Kiremt*), which begins in April/May in the Eastern and Western highlands (e.g. Sagure and Butajira, respectively) and in June in the Central lowlands (e.g. Zeway) (Fig. 2). The long rainy season ends almost uniformly across the CRV in October. The length of growing period (LGP) is shorter in the lowlands than in the highlands due to the later onset of the long rainy season. Rainfall in the short rainy season is generally insufficient to produce a crop and the long rainy season is therefore the main production season for most farmers. About 70% of the annual rainfall precipitates in the main rainy season. The annual average daily temperature varies from about 16°C in the Eastern and Western highlands (3000 m a.s.l.) to 21°C in the Central lowlands (1600 m a.s.l.).

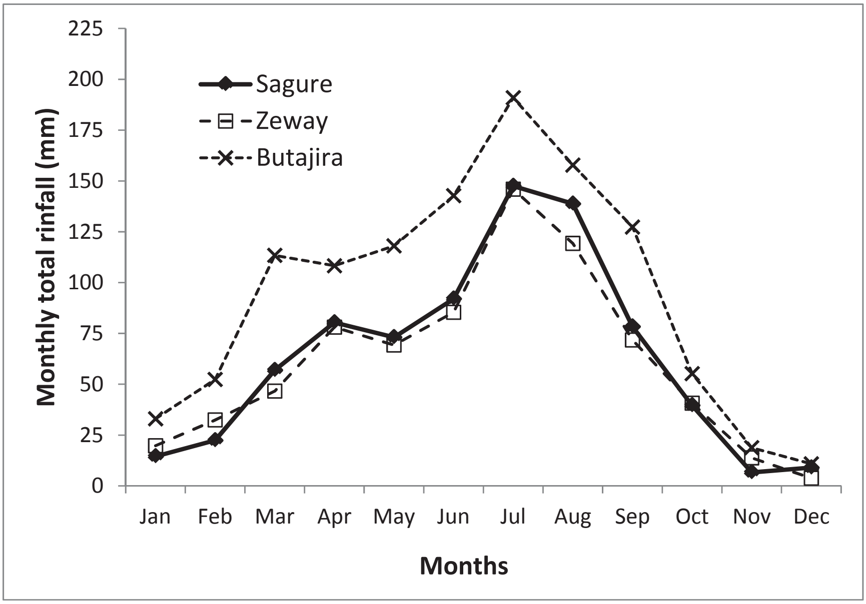

Figure 2. Monthly rainfall distribution of Sagure, Zeway and Butajira weather stations representing the Eastern highlands, Central lowlands and Western highlands, respectively, of the Central Rift Valley in Ethiopia (Data source: National Meteorological Agency, 1990-2009).

The main part of the CRV (ca. 54%) is located on relatively flat land with slopes of less than 8%, potentially allowing both rainfed and irrigated agriculture. The remainder, ca. 20% of the CRV, is characterised by slopes of 8-16%, potentially suitable for rainfed agriculture and for pressurized irrigation. Approximately 18% of the CRV is on slopes of more than 16%, which are not suitable for sustainable arable farming without making huge investments in conservation structures, and the remaining 8% is covered by lakes.

Eight major soil types are found in the CRV, Luvisols (42%) are the most dominant soil type, while Nitisols (12%), Andosols (10%), Cambisols (10%) and Vertisols (8%) also cover large areas in the CRV.

Cultivated land is the dominant land use (ca. 70%) in the CRV, while ca. 17% consists of natural and semi-natural vegetation (e.g. forests, grasslands) and 13% is not suitable for agriculture (e.g. built-up area, degraded land) (Getnet et al., 2014). Cereals are the dominant crops in the CRV with maize and wheat occupying ca. 26 and 24% of the total cultivated area, respectively (IFPRI, 2006).

2.2 Concepts and the methodological approach

We followed the production-ecological approach to analyse yield gaps (Van Ittersum and Rabbinge, 1997). The approach explains potential, limited and actual production levels (the levels of primary output per unit area) as function of yield defining, yield limiting and yield reducing factors, respectively (Fig. 3).

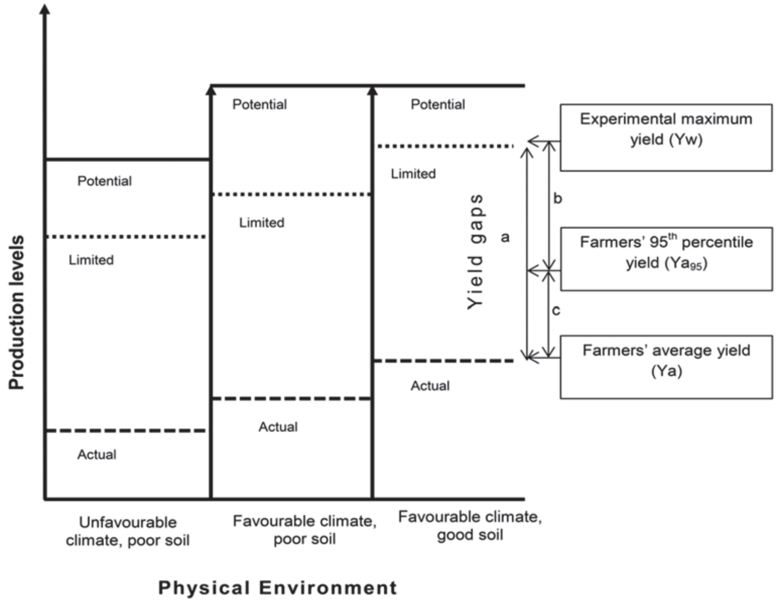

Figure 3. The production-ecological approach that explains potential, limited (Yw) and actual (Ya) production levels and the yield gap (a= between Yw and Ya; b= between Yw and Ya_{95}; and c=between Ya_{95} and Ya) as function of yield defining, limiting and reducing factors under various physical environments based on Van Ittersum and Rabbinge (1997).

Potential yield (Yp) is the theoretical yield obtained for yield defining factors (radiation, temperature and crop characteristics) of a given physical environment while water and nutrients are supplied optimally and pests and diseases are fully controlled.

Water-limited and/or nutrient-limited production levels (Yw or Yn) are attained at lower levels than the potential because of suboptimal supply of water and/or nutrients, respectively. Both Yp and Yw are calculated for optimum or recommended sowing dates, planting density and variety (Van Ittersum et al., 2013). Sowing dates and the maturity period of varieties should fit with the dominant cropping system and the feasible growth duration, particularly in tropical and semi-tropical environments, where the length of the growing season shows a strong spatial variation.

The actual production level (Ya) is determined by the degree to which a crop is exposed to yield reducing factors (weeds, diseases and pests) together with the effects from yield defining and yield limiting factors. The actual yield is influenced by the actual agronomic management practices to overcome the impacts of yield limiting and reducing factors.

The yield gap (Yg) can be defined as the difference between Yp (modelled or measured in well-managed irrigated experiments) and Ya. In rainfed systems, Yw is the most relevant benchmark to calculate yield gaps (Van Ittersum et al., 2013). While Ya can be estimated from the mean or median of farmers' average production (Van Ittersum et al., 2013), maximum yields under controlled conditions (on-station, under optimum conditions with no nutrient limitation and yield reduction due to pests and diseases) can represent Yw (Tittonell and Giller, 2013; Van Ittersum et al., 2013). The average yield from such experiments over many years reflects a typical range of climate variation and thus represents a robust estimate of Yw (Lobell et al., 2009). Therefore, yield gaps and resource use efficiencies were determined for multiple years using a framework of analysis (Fig. 4). Similar to the use of Ya and Yw for the calculation of yield gaps, RUEs of rainwater, N and P fertilisers have been determined at two levels: the actual production level that is represented by farmers' average yield and the water-limited production level derived from experiments.

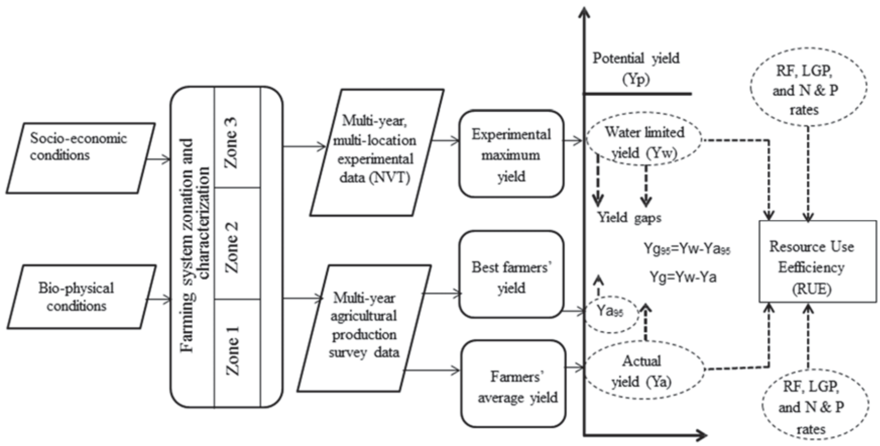

Figure 4. Framework for analysis of yield gaps and resource use efficiency in the Central Rift Valley (CRV); NVT: National Variety Trial; RF: Rainfall; LGP: Length of Growing Period; N: Nitrogen; P: Phosphorus.

As yield gaps and RUEs vary across locations because of the interactions between genotype, environment and management (G x E x M), we cannot treat the entire CRV as one unit of analysis. We therefore distinguish farming zones with relatively homogeneous environmental and management characteristics (Homogenous Farming Zone-HFZ).

2.3 Data

For the farming zonation socio-economic information of the 11 districts of the CRV was obtained from the Atlas of Ethiopian rural economy (IFPRI, 2006). Rainfall and temperature data from 17 weather stations were obtained from the National Meteorological Agency (NMA) (Table 1). These data were interpolated and district level averages were used in the farming zonation (Table 2). Daily rainfall data (2004-2009) from three representative weather stations (Zeway, Sagure and Butajira) was used for calculating seasonal rainfall and rainfall water use efficiency (WUE) per HFZ (Table 3).

Experimental yield data (at grain moisture content of 12.5%) of National Variety Trials (NVTs) (2004-2009) of the Ethiopian Institute of Agricultural Research (EIAR) were obtained from various sites representative for the study area (Table 1) to estimate Yw (see below for justification and more information). The NVT data are averages of three replications and comprise yields of about 12 candidate varieties and three released (control) varieties.

Farm data to estimate Ya was acquired from the Central Statistics Authority (CSA). The agricultural database contains annual information on ca. 1800 farmers' fields of wheat and maize from 2004 to 2009 (total of 10,756 fields over six years) within our study area. Besides the field location, the information includes the area and grain yield of surveyed fields (measured at harvest), type and amount of fertiliser applied, and farmers' perceptions on the presence or absence of erosion (yes/no) of each surveyed field. The survey data by CSA is based on a stratified two-stage sampling design in which enumeration areas (smallest boundaries used by CSA to administer surveys and censuses) are primary sampling units and agricultural households are secondary sampling units. Data on field size is obtained by physically measuring the fields of sampled households. Yield data is collected from a 4 x 4 m quadrant that is laid in the middle of sampled fields using pegs, immediately after planting. The quadrant receives similar farmer's management as the rest of the field whereas farmers agree not to harvest any plants at green stage (particularly for maize) from within the quadrant. The harvested crop is threshed, sundried and regularly weighed until a constant weight is attained for reporting. Sundried moisture content may slightly differ from the 12.5% grain moisture content at experimental fields though the error is expected to be small. Data on input use is obtained by interviewing the sampled households about their farm operations during the season. Input rates are calculated on a hectare basis based on the measured field size.

Because district boundaries and variable names in the CSA survey data had changed over the years, we improved the consistency of the data to enable time series analysis by (1) spatially reassigning farm data to districts using consistent district boundaries; and (2) standardizing variable names using the field code books used in each survey year by CSA.

Table 1. Description of data used to estimate yield gaps of maize and wheat and related resource use efficiency of actual and water-limited yield.

		Description
Survey data (to estimate Ya, Yg and RUE)	Source	Central Statistical Authority (CSA) of Ethiopia
	Crops	Maize and wheat
	Data used	Field size (ha) and production(kg) (to derive grain yield), fertiliser types (DAP, urea, manure), fertiliser rate (kg ha^{-1}) for DAP and urea
	Number of field-year combinations	10,756 (622, 2733, 3183 for maize, and 1270, 1578 and 1370 fields for wheat in the Eastern highland, Central lowland and Western highland zones, respectively)
	Period	2004-2009
	Resolution	Field level
Experimental data (to estimate Yw, Yg and RUE)	Source	Ethiopian Institute of Agricultural Research (EIAR)
	Crops	Maize and wheat
	Data used	Grain yield (t ha^{-1}) (average of three replications), fertiliser use (kg DAP and/or urea ha^{-1})
	Representative EIAR experimental locations	[Kulumsa, Sagure, Bekoji, Sinana, Bako, Kofele, Arsi-Robe][1], [Melkassa, Zeway, Dehra, Goro, Assasa, Siraro, Meisso][2] [DebreZeit, Ginchi, Holeta, Areka, Kokate, Hawassa][3]
	Period	2004-2009
	Number of variety-location-year combinations	134, 315, and 134 for maize, and 466, 324 and 334 for wheat representative for the Eastern highlands, Central lowlands and Western highlands, respectively.
	Nature of experiment	National Variety Trials, ca. 15 candidate/ released varieties per location in three replications; plot size 7.5 m^2 for maize and 3 m^2 for wheat
	N & P rate per ha for maize	100 kg N and 44 kg P for the Eastern and Western highlands; 41 kg N and 20 kg P for the Central lowlands*
	N & P rate per ha for wheat	50 kg N and 30 kg P for the Eastern and Western highlands; 41 kg N and 20 kg P for the Central lowlands *
	Source of nutrient	DAP and Urea
Rainfall data (to estimate WUE)	Source	National Meteorological Agency (NMA) and EIAR
	Data used	Rainfall data used to define onset and end dates, and calculate seasonal total rainfall for representative weather stations per HFZ.
	Period covered	2004-2009
	Resolution	Daily
	Weather station	Sagure (Eastern highland), Zeway (Central lowland) and Butajira (Western highland)

[1] Research centres/ experimental sites that usually target varieties and other agricultural technologies to the Eastern highlands of CRV; [2] for the Central lowlands; and [3] for the Western highlands. RUE: resource use efficiency, WUE: rain water use efficiency. * application rates on experimental fields based on recommendations for similar environmental conditions in Ethiopia.

2.4 Farming zonation

Although the CRV is a small basin relative to the larger Rift Valley Lakes Basin and other basins in Ethiopia, biophysical and socioeconomic conditions are heterogeneous especially related to altitude and climate, which necessitates a zonation. Raster maps were produced for rainfall, temperature and altitude of CRV, based on which the average rainfall, temperature and altitude was calculated as physical indicators for each of the 11 districts using ArcGIS10. A hierarchical cluster analysis was conducted using the nine physical and socioeconomic indicators (Table 2) to classify the districts in the CRV into relatively homogeneous farming zones (HFZs).

Table 2. Socioeconomic and physical indicators used to group districts into relatively homogeneous farming zones. The first six socioeconomic indicators are district level averages (IFPRI, 2006), the last three indicators are calculated averages of raster values per district.

	Districts in Central Rift Valley										
Indicator:	DB	AT	AN	ZD	DT	Ty	Mu	Bk	Sd	MM	Sl
Crop area per holder (ha)	1.8	1.2	1	1.4	1.3	1.4	1.3	1.4	0.7	0.5	0.5
Holding fragmentation[1]	1.9	1.7	1.9	2.4	2	2	1.8	1.9	2.8	4.2	3.9
% permanent crop area[2]	0.31	0.01	1.03	0.0	0.14	0.4	0.33	0.0	11.2	11.5	13.4
% holders with < 1 ha[3]	34	44	50	38	38	38	36	32	72	85	82
Cattle herd size per holder	7.3	6.5	6.2	5.8	5.5	4.7	6.4	6.8	4.2	3.4	3.7
Population density (km^{-2})	122	125	139	90	142	268	129	150	177	359	304
Mean temperature (°C)	19.4	19.9	19.3	19.3	15.5	16.0	18.0	15.7	17.8	18.2	18
Mean annual rainfall (mm)	817	747	882	796	1015	966	995	1206	1005	993	980
Mean elevation (m a.s.l.)	1708	1654	1803	1795	2840	2562	2447	2792	2145	2024	2072

[1] The average number of parcels per holding; [2] Permanent crop area as a percentage of cropped area; [3] Percentage of holders who have land holding size of 1 hectare or less. DB=Dugda Bora; AT= Adami Tulu; AN= Arsi Negele; ZD=Zeway Dugda; DT= Degelona Tiyo; Ty= Tiyo; Mu= Munessa; Bk=Bekoji; Sd=Sodo MM=Meskanena Mareko; Sl= Selti. m a.s.l.= meters above sea level

2.5 Estimation of yield gaps

Yield gap analysis was performed for rainfed maize and wheat in the identified HFZs for each year from 2004 to 2009 to capture climate variability, and then the average Yg per HFZ across the six years was computed. We considered the crops maize and wheat for three reasons. First, both crops grow across the different landscapes of the CRV, facilitating the comparison of yield levels between the three HFZs. Second, they are the most important cereals in terms of land use in the CRV. Third and related to the previous two issues is the data availability of both crops.

We estimated Ya as the average yield (t ha^{-1}) from farmers' fields per HFZ based on the CSA survey data for every year in the period 2004-2009. We conducted descriptive statistics and mean comparison on Ya and associated nutrient use (N and P) across the HFZs. The Kruskal-Wallis test for non-normally distributed data was used to test the significance of the difference in Ya between the three HFZs. We used the Mann-Whitney U test (non-parametric) to compare two groups, i.e. (1) yields of fertilized and unfertilized fields, (2) yield as well as N application rates of fields with and without perceived erosion problems. Furthermore a Chi-square test was applied to understand the association between fertiliser application (0=no, 1=yes) and perceived presence of soil erosion (0=no, 1=yes). We also calculated the 95^{th} percentile of farmers' yields (Ya_{95}) for the same period as a yield indicator of best performing farmers. We compared the yield and mean nutrient applications at Ya_{95} with those of Ya production levels. Because the sample size of the latter group was much larger, we randomly selected the same number of observations as in the Ya_{95} sample to enable a t test for nutrient use on equal sample size. Finally, we selected all farmers' fields that received N input rates greater or equal to the recommended rates, computed the average yields from these fields by HFZ and compared these with the yields from fields that received less than the recommended rates.

National Variety Trial (NVT) yield data from representative locations in HFZs (Table 1) were pooled for each of the years 2004-2009. The maximum of the experimental yield from each year in each HFZ is used to represent Yw of the particular year and HFZ. The annual Yw values were plotted to show the Yw trend over six years. We also computed the variation in Yw across HFZs.

The annual yield gap is computed as the difference between water-limited (Yw) and actual yield (Ya) levels of corresponding years, and the average (2004-2009) is presented by crop and HFZ to represent Yg of an average year. Similarly, we computed the difference between Yw and Ya_{95} as an indication of the yield gap between water-limited potential and best farmers' yield across HFZs (Yg_{95}; Fig. 4). Finally, we compared Yw with the Ya of fields receiving at least the recommended N application rate to assess the single effect of N input on narrowing the yield gap.

Our assumption that the maximum trial yield (average from three replications) for any given HFZ represents the Yw is based on the fact that the varieties tested include the optimum varieties for the region and input use is assumed close to optimal. Also the agronomic management aspects are optimized: sowing dates and planting densities are such that maximum yields may be expected, weeds are controlled by intensive and timely hand weeding (using skilled, hired labour) and herbicides, whereas diseases and pests are controlled by chemical spraying. However, two reservations must be made regarding the assumption about Yw. First, the fertiliser application is limited to DAP and urea, so only N and P are applied, while other nutrients may have limited production. Secondly, the NVTs received a locally recommended N and P rate, which is a blanket recommendation for large areas regardless of the soil fertility status of individual fields. Therefore, the applied N and P rate in some of the NVTs may have been suboptimal for achieving Yw, and thus the calculated yield gap might underestimate the real yield gap. On the other hand, farmers use a range of varieties including open-pollinated and hybrids, but some of the new varieties in the NVT may not be available to the farmers in the same year. This may be a reason for an overestimation of the real yield gap using NVTs.

2.7 Estimation of resource use efficiencies

The survey database from CSA lacks data on planting and harvesting dates impeding the calculation of the growing season rainfall. Therefore, the start and end of the main rainy season were calculated for the years 2004 -2009 for three weather stations, Butajira, Zeway and Sagure, which are representative for the Eastern highland, Central lowland and Western highland zones, respectively. The start of a growing season is the first day of the year when cumulative rainfall from three consecutive days is 20 mm or more and is not followed by a dry spell of eight consecutive days or more during the subsequent 30 days (Segele and Lamb, 2005; Sivakumar, 1988). The end of the season is defined as the first day of a dry period (<0.1 mm day^{-1}) of at least 20 days occurring after onset of the season. The total rainfall received between the start and end of the season (RF_{LGP}) was calculated for each year.
Rain water use efficiency (WUE) of each year in the period of 2004-2009 is estimated corresponding to Yw and Ya as (Eq. 1):

$$WUE = Y/RF_{LGP} \quad \text{Eq. 1}$$

Where WUE = rain water use efficiency (kg ha^{-1} mm^{-1}); Y = grain yield (kg ha^{-1})- either Yw or Ya; RF_{LGP} = total rainfall (mm) within the growing season.

We are aware that the actual planting of some fields is usually done after the onset of the rainy season because inputs (e.g. fertiliser) and labour may not be available to timely plant all fields at the same moment. Yet, we assume that also the rainfall (after the onset of the season) that is received before actual planting is available for the crop as soil moisture. Therefore, any delay of planting for whatever reason is attributed to the inefficiency of the farmer in using the available moisture; hence we used RF_{LGP} to allow a consistent comparison of WUE between the farmers' and experimental situations.

The survey database comprises data on the amount (kg) of DAP, urea or both applied on each field. We expressed fertiliser use in terms of N and P based on the relative percentage of these nutrients in the fertilisers. For few fields, i.e. ca. 7% of the 10,756 maize and wheat fields, the total amount of DAP and urea applied per field is presented as one aggregated value in the database. In these cases, a 2:1 ratio of DAP and urea (based on the blanket recommendation of N and P in most parts of CRV) was assumed, to calculate the applied amounts N and P.

The actual yields from fields without and with N application are compared as an indicator of the agronomic N use efficiency. Fields that received organic fertiliser (manure) are excluded from this analysis as quantitative information on the amount and quality of the manure was lacking, whereas it may have influenced yields.

3. Results

3.1 Homogenous farming zones

The major heterogeneity within the CRV was captured by grouping the eleven districts (Table 2) into three relatively homogenous farming zones (Table 3) facilitating the analysis of yield gaps and resource use efficiencies.

The districts Degelona Tiyo, Bekoji, Tiyo and Munessa are grouped in the Eastern highland zone with a relatively early onset of the rainy season and the highest proportion of seasonal to annual rainfall (Table 3). This zone is a cereal mixed farming zone at high altitude characterised by relatively low temperatures. Major cultivated crops include wheat (*Triticum spp.*) and barley (*Hordeum vulgare*) whereas faba bean (*Vicia faba*), maize (*Zea mays*), sorghum (*Sorghum bicolor*), rape seed (*Brassica campestris*), flax (*Linum usitatissumum*) and mustard (*Brassica juneca*) are also grown. The latter three crops are mostly grown in rotation with wheat and barley.

The districts Arisi Negele, Zeway Dugda, Dugda Bora and Adami Tulu are in the Central lowland zone with the latest onset of the season and the lowest annual and seasonal rainfall (Table 3). Temperatures are relatively high at this low altitude zone around the lakes Zeway, Langano and Abyata. In the dominant mixed farming systems maize, tef (*Eragrostis tef*) and wheat are major staple crops, while haricot bean (*Phaseolus vulgaris*) is often grown as a cash crop.

The districts Maskanena Mareqo, Silti and Sodo are grouped in the Western highland zone, which is characterised by the lowest proportion of seasonal to annual total rainfall (and highest seasonal total rainfall) with a relatively early onset of the rainy season (Table 3). The Western highland is an Enset based mixed farming zone where tef, wheat, maize, faba bean, haricot bean and chilli (*Capsicum fructescens*) are mono-cropped or intercropped with Enset (*Ensete ventricosum*).

Table 3. Agro-meteorological characteristics of three homogeneous farming zones (HFZs).

HFZ [1]	Districts in the HFZ	Representative weather station	Average onset date of rainy season	Average end date of rainy season	Mean annual rainfall	Seasonal rainfall [2]	
						Total (mm)	% [3]
EH	Degelona Tiyo, Bekoji, Tiyo, and Munissa	Sagure	24-Apr	1-Nov	772	639	83
CL	Arsi Negele, Zeway Dugda, Dugda Bora and Adami Tulu	Zeway	7-Jun	10-Oct	752	509	68
WH	Meskanina Mareko, Selti and Sodo	Butajira	28-May	17-Oct	1151	731	64

[1] EH= Eastern highlands, CL = Central lowlands, WH = Western highlands; [2] Seasonal rainfall refers to the rainfall between the mean onset and end date; [3] seasonal rainfall as a percentage of annual total rainfall.

3.2 Current maize and wheat yields and fertiliser use

Median maize yields recorded on farmers' fields are highest in the Central lowland zone (2.43 t ha^{-1}), relative to the Western highland (2.02 t ha^{-1}) and Eastern highland zones (1.89 t ha^{-1}) (Fig. 5). Median wheat yields are similar in the Eastern highland (1.93 t ha^{-1}) and Central lowland zones (1.94 t ha^{-1}) whereas they are lowest in the Western highland zone (1.65 t ha^{-1}).

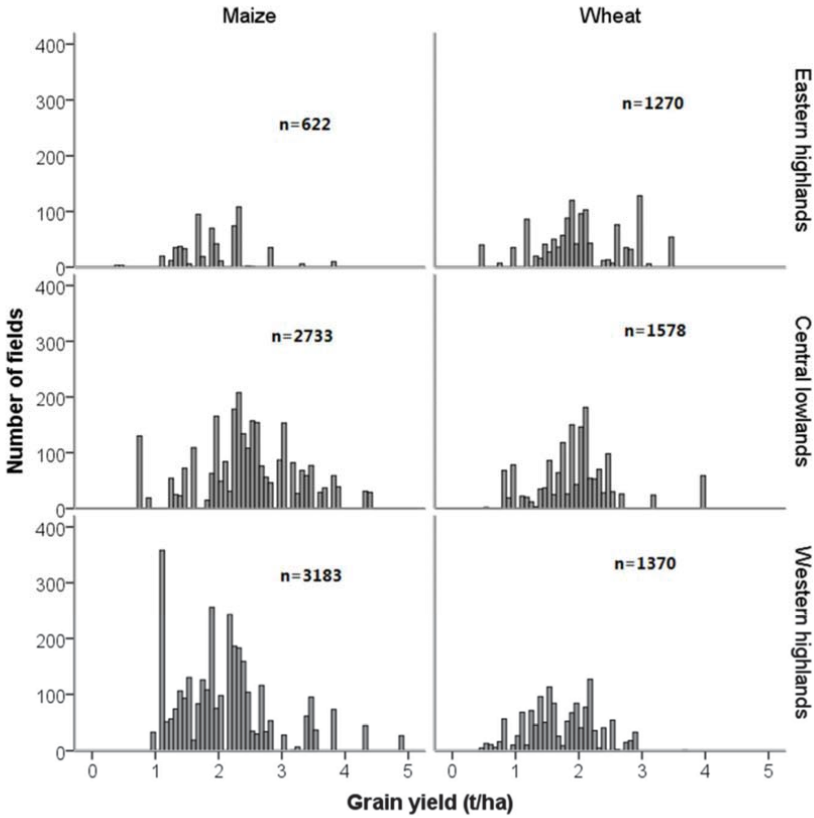

Figure 5. Frequency distribution of the actual yield levels of maize and wheat in the three HFZs based on survey data from CSA for the period of 2004-2009 (N=10,756). Grain yield is measured after sundried to a constant weight level.

Relatively more maize than wheat fields received organic fertiliser (dominantly manure and in a few cases compost). Out of the surveyed maize fields over six years in the CRV (n=6527) 32% received only organic fertiliser, 17% only mineral fertilisers, and 5% received both. Of the surveyed wheat fields in the period 2004-2009 (n=4213) 5% received only organic fertiliser, 66% only mineral fertilisers, 2% received both. A large proportion of maize (46%) and wheat (27%) fields did not receive any fertiliser.

The overall average N and P mineral fertiliser application rates on maize and wheat fields in the CRV were generally low (2.6-16.5 kg N ha^{-1} and 2.2-17.3 kg P ha^{-1} across HFZs and crops) but relatively higher for wheat than for maize across the HFZs (Fig. 6a,b). The N and P application rates on maize were highest in the

Western highland zone, while for wheat the rates were highest in the Eastern highland zone (Fig. 6a,b). Taking into account only those fields that received mineral fertilisers, the average N rates were below 30 kg ha^{-1}, which is much less than the recommended rate of 100 kg ha^{-1} for maize in Eastern and Western highlands. Actual P application rates of those fields that received mineral P were near 20 kg ha^{-1} across HFZs and crops (Fig. 6c,d), which is close to the recommendation (Table 1).

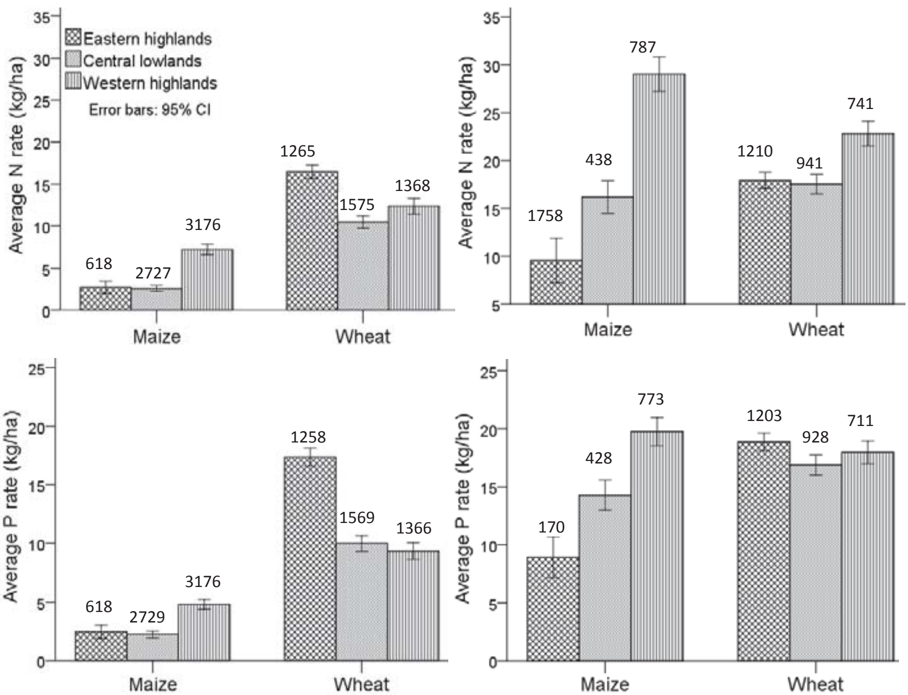

Figure 6. Farmers' nitrogen and phosphorous fertiliser rates in maize and wheat in the three farming zones of the Central Rift Valley based on survey data (CSA, 2004-2009): (a) average N rate based on all fields; (b) average P rate based on all fields; (c) average N rate of fields that received N fertiliser; and (d) average P rate of fields that received P fertiliser. Numbers above bars are the sample sizes.

3.3 Yield gap

Trends in Ya, Yw and Yg

For both crops, Yw estimated from the NVTs was more variable across years than Ya (i.e. CVs of Yw were ca. 28% for maize and 22% for wheat, and of Ya ca. 20% for maize and 16% for wheat) (Fig. 7). We did not find a significant association between seasonal rainfall and Yw (data not shown).

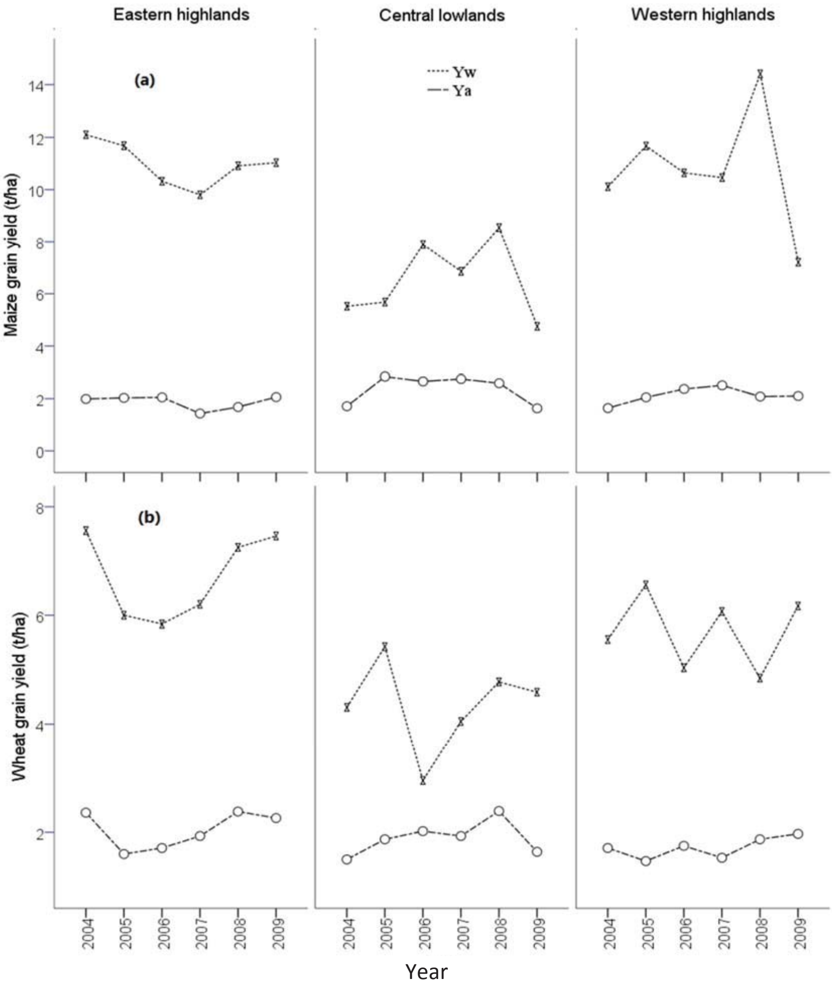

Figure 7. Trends in actual and water limited yield of maize (a) and wheat (b) in the three homogeneous farming zones of the Central Rift Valley from 2004 to 2009.

The CRV average actual yield (Table 4) of maize (2.12 t ha^{-1}) was close to the national average (CSA, 2007), and that of wheat (1.88 t ha^{-1}) was larger than the national average for the same period (2004-2009), i.e. 2.10 and 1.62 t ha^{-1} for maize and wheat, respectively. The percentage of Ya relative to Yw in the CRV was generally low indicating a wide yield gap. This percentage was highest in the Central lowland zone (36% and 43% for maize and wheat, respectively) compared to 17% (maize) and 30% (wheat) in the Eastern highland, and 20% (maize) and 30% (wheat) in the Western highland zones. The Central lowland zone is characterised by the lowest Yw and Yg for both crops (Fig. 7; Table 4). Average maize yield from best performing farmers (Ya_{95}) was about 1 t ha^{-1} higher than Ya in all HFZs, whereas for wheat the difference was about 0.8 t ha^{-1}. This indicates that for both crops there is much scope for yield improvement also for the best performing farmers.

Table 4. Average actual yield, yield of best performing farmers, water-limited yield (2004-2009) and yield gaps for maize and wheat in the three homogeneous farming zones (HFZs) of the Central Rift Valley of Ethiopia.

		Yield (t ha^{-1})			Yield gap (t ha^{-1})	
crop	HFZs	Ya	Ya_{95}	Yw	Yg = Yw-Ya	Yg_{95} = Yw- Ya_{95}
Maize	Eastern highlands	1.87	2.75	10.97	9.10	8.23
	Central lowlands	2.36	3.35	6.54	4.18	3.19
	Western highlands	2.13	3.41	10.75	8.63	7.35
	Average of HFZs	2.12	3.17	9.42	7.30	6.25
Wheat	Eastern highlands	2.04	2.79	6.72	4.68	3.93
	Central lowlands	1.89	2.63	4.35	2.46	1.73
	Western highlands	1.72	2.51	5.71	3.99	3.2
	Average of HFZs	1.88	2.64	5.59	3.71	2.95

Ya= actual yield; Yw = water-limited yield; Ya_{95}= the 95th percentile of farmers' yield; Yg= yield gap between water-limited and actual yields; Yg_{95}= the yield gap between the water-limited and best farmers' yield (represented by 95th percentile of farmers' yield) levels.

3.4 Resource use efficiency

The WUE of Ya across HFZs ranged between 2.7-4.3 kg ha^{-1} mm^{-1} of seasonal rainfall for maize, and between 2.3-3.5 kg ha^{-1} mm^{-1} for wheat. Compared to that, the WUE associated with Yw was much higher, i.e. 12-17.3 kg ha^{-1} mm^{-1} for maize and 7.4-10.6 kg ha^{-1} mm^{-1} for wheat (Table 5). The WUE of Ya was higher in the

Central lowland zone, where seasonal rainfall was lower than in Eastern and Western highland zones.

The yield difference between fields with mineral N application and fields without was very small in most HFZs and even negative in some HFZs (Table 5). Approximately 95% of the wheat and maize fields that received mineral fertiliser received less N than the recommended fertiliser rate, whereas ca. 80-93% (ranging between HFZs) of maize and 75-85% of wheat fields received less P than the recommended rate (Fig. 8). There was a large variation in nutrient application rates and yield within and between years and no clear relationship between mineral N and P application rates and yields (Fig. 8). However, farmers who applied the locally recommended N rate or more (right of the vertical line in Fig. 8) obtained some yield gain in most HFZs. The yield gain was 22% in Eastern highlands and 6% in Central lowlands for maize; and 28% in Central lowlands and 7% in Western highlands for wheat as compared to the farmers that applied less than the recommended rate. There was no yield increase for maize in Western highlands and wheat in Eastern highlands.

The average mineral N and P application rates of Ya_{95} were significantly higher than the rates used by the average farmer population ($p<0.001$) for both maize and wheat fields. On average, best performing farmers applied ca. 8-20 kg N ha^{-1} and 5-21 kg P ha^{-1} (ranges across HFZs and crops). For example, on wheat the N application rate was ca. 20 kg ha^{-1} for Ya_{95} as compared to 12 kg ha^{-1} for Ya.

Table 5. Rain water use efficiency for actual (Ya) and water-limited (Yw) maize and wheat yields, and actual maize and wheat yields of fields without and with nitrogen application in three homogeneous farming zones (HFZs) of the Central Rift Valley of Ethiopia.

Crop	HFZ	WUE		Average N input to Ya (kg ha^{-1})	Ya (t ha^{-1})	Ydiff (t ha^{-1})
		Ya (kg mm^{-1})	Yw (kg mm^{-1})			
Maize	EH	2.9	17.3	0	2.13	
				10	1.75	-0.38
	CH	4.3	12.0	0	2.66	
				16	2.72	0.06
	WH	2.7	13.9	0	2.25	
				29	2.20	-0.05
Wheat	EH	3.2	10.6	0	1.98	
				18	1.94	-0.04
	CH	3.5	7.9	0	1.86	
				18	2.14	0.28
	WH	2.3	7.4	0	1.73	
				23	1.74	0.01

WUE is computed based on seasonal total rainfall of HFZs and Ya and Yw yield levels (Table 5). Ya=actual yield; Yw= water limited yield; Ydiff = difference between Ya with and without fertiliser application; HFZ=homogeneous farming zones; EH=Eastern highlands; CL=Central lowlands; WH= Western highlands

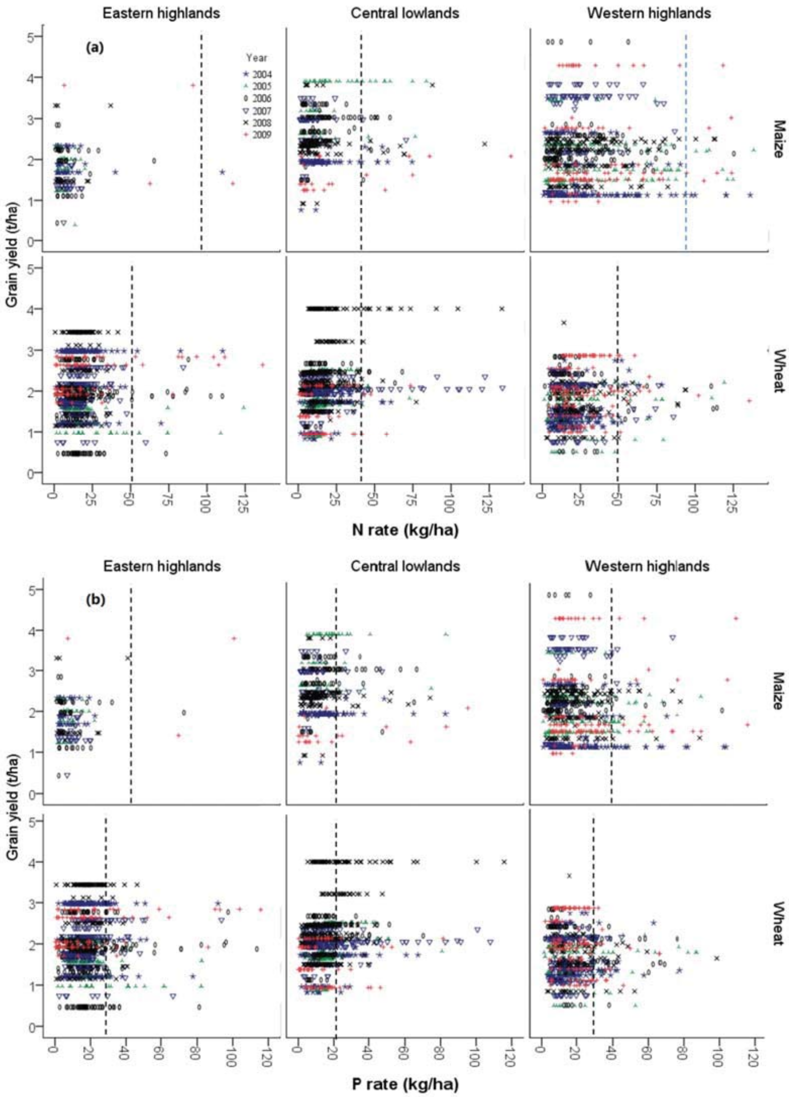

Figure 8. Scatterplots of actual nutrient application rates and grain yields of maize and wheat in three homogenous farming zones of the Central Rift Valley of Ethiopia. (a) Nitrogen and (b) Phosphorus. Dashed vertical lines indicate the N and P application rates used in experimental plots of National Variety trials across HFZs based on the "blanket recommendation rates" of N and P.

Out of the maize and wheat fields for which the erosion status was recorded (n=8494), about 60% were perceived by farmers to have soil erosion problems. Furthermore, about 67% of the maize and wheat fields that received mineral N were reported to have soil erosion problems indicating that N application may be confounded with the perceived erosion status of the field, i.e. farmers prioritize fertilization of fields with erosion problems.

4. Discussion

4.1 Yield gaps and scope for production increase

Our estimates of Ya, ranging across HFZs between 1.9 – 2.4 t ha^{-1} for maize and 1.7 - 2.0 t ha^{-1} for wheat, are in a good agreement with other estimates (Adimassu et al., 2013; GYGA, 2014; Howard et al., 2003; Kassie et al., 2014b). Average yield gaps of maize (7.3 t ha^{-1}) and wheat (3.7 t ha^{-1}) in the CRV are large. Yg varies across years and HFZs in the CRV, which is mainly associated with a variable Yw (rather than Ya). In the NVTs nutrients and pests and diseases are controlled, so that the effects of seasonal rainfall variability on Yw are more pronounced. Furthermore, Ya is the average of a large number of fields (Table 1) whereas Yw is derived from a limited number of experiments. There was no relationship between rainfall and Yw, which may be because climate parameters were derived from a single representative weather station per HFZ, whereas yield data from several experimental stations were used (Table 1).

Lower rainfall and higher temperature in the Central lowlands result in lower Yw and hence lower Yg for both crops as compared to the other HFZs. Furthermore, maize Ya (also as a percentage of Yw) is relatively high (Table 4), as in this zone maize is the major food crop (Table 6) that receives relatively good management, such as weed control.

Maize Yg for the Central lowlands in this study (4.2 t ha^{-1}) was a bit lower than the 4.7 and 5.5 t ha^{-1} at Melkassa and Zeway estimated from a model and average farm yields from reports (Kassie et al., 2014b). Our estimated maize Yg (Table 4) is within the range of calculated Yg in the Global Yield Gap Atlas (www.yieldgap.org; 6.4-10.4 t ha^{-1}), except for the Central lowlands, for which Yg is considerably lower in our study. Our estimated Yg for wheat (Table 4; 2.5-4.0 t ha^{-1}) is lower in all HFZs than in the Global Yield Gap Atlas (5.2-7.6 t ha^{-1}), pointing at sub-optimal conditions in the NVT trials, particularly with respect to fertilization, both in terms of types of nutrients (only N and P) and quantities (see Material and Methods).

Across the HFZs Ya is only ca. 17-36%, and 30-43% of Yw for maize and wheat, respectively. Increasing the actual yield to a level equivalent to Ya_{95} narrows the yield gap of both maize and wheat by ca. 10-15%. Though the percentage looks small, the difference between Ya and Ya_{95} is significant and is related to a higher N and P input use in Ya_{95} fields for both crops ($p<0.001$). For example, the N application rate on wheat was ca. 20 kg ha^{-1} for Ya_{95} as compared to 12 kg ha^{-1} for Ya.

Applying locally recommended N rates or more under current farmers' management (right of the vertical line in Fig. 8), narrowed the maize and wheat yield gap by less than 5% in most HFZs. For wheat in the Central lowlands ca 22% of the yield gap can be narrowed by applying the recommended N rate (or more). For maize in the Western highlands and wheat in the Eastern highlands, where the actual N rates were relatively larger (Fig. 6), the yield gap remained the same for farmers who applied the locally recommended N rate or more, and farmers who applied less than the recommended N rate.

The large remaining part of the yield gap results from differences between farmers' fields and experimental fields in terms of crop management practices, including differences in varieties, seed, planting (date, method and density), weeds, pests and disease control, and timing of farm operations. Unlike experiments with improved open pollinated (OPV) and hybrid varieties from good quality seed, most farmers use local varieties, a few farmers use improved OPV (mostly recycled seed), and very few use hybrids. Contrary to experiments with timely and row planting, farmers typically broadcast seeds (particularly wheat) and delay sowing because of competition for scarce resources (e.g. family labour and draught power), and the fear for early-season dry spells. Such delay in planting often reduces the yield and resource use efficiency, and farm resource limitations (e.g. labour, equipment, capital) further impede overcoming yield-reducing factors (e.g. weeds, pest and diseases) compared to the experimental fields where skilled labour and chemicals are used for crop protection. In this respect, the best performing farmers, who achieve significantly smaller yield gaps than their "average neighbours" may illustrate how higher nutrient input and better crop management raise yields. Taking the actual crop area (IFPRI, 2006), and maize and wheat yields in each HFZ as a benchmark, lifting Ya to Ya_{95} or to the exploitable yield level (80% of Yw – Cassman et al., 2003; Van Ittersum et al., 2013) would result in a 50 to 175% production gain, respectively. Attaining the Yw level would result in a production increase of 240% for maize and 255% for wheat (Table 6) in the CRV. Enormous investments are required in human capacity, infrastructure and agricultural technology to attain this increase. This, however, remains difficult under the current socio-economic conditions in which more than 50% of the crop farmers own less than one ha of land (IFPRI, 2006), ca.

90% of the fields are cropped with local seed, 50-60% of the households are illiterate and many farmers have limited financial capacity to purchase inputs (IFPRI, 2013). Clearly, under variable rainfall conditions it is also risky to increase input levels.

Table 6. Potential for production increase of maize and wheat in the three homogeneous farming zones (HFZs) of the Central Rift Valley of Ethiopia as a result of achieving different target yields, i.e. best farmers' yield (Ya_{95}), 80% of the water-limited yield (80% Yw) and water-limited yield (Yw). Between brackets the percentage gain relative to the actual production.

		Actual crop:*		Possible production gain (kt) using different yield targets:		
Crop	HFZ	Area (000 ha)	Production (kt)	Ya_{95}	80% Yw	Yw
Maize	EH	6.5	13.9	5.6 (40)	44.7 (321)	58.9 (423)
	CL	61.0	144.2	60.4 (42)	175.3 (122)	255.1 (177)
	WH	17.5	35.5	22.5 (63)	113.5 (320)	151.4 (427)
	CRV total	85.1	193.6	88.5 (46)	333.5 (172)	465.5 (240)
Wheat	EH	58.8	100.3	44.1 (44)	196.1 (195)	275.1 (274)
	CL	21.8	29.7	15.9 (54)	34.7 (117)	53.7 (181)
	WH	6.4	9.0	5.1 (56)	18.4 (204)	25.7 (285)
	CRV total	87.1	139.1	65.1 (47)	249.2 (179)	354.5 (255)

* Actual crop *area* is the total area allocated to maize and wheat in each HFZ of the CRV, and the total *production* from the respective area (IFPRI, 2006). Possible production gains at various target yield levels are calculated based on the respective yield gap (Table 5). The '80%' of Yw is the so-called exploitable yield gap (Cassman et al., 2003; Van Ittersum et al., 2013).

4.2 Resource use and resource use efficiency

The rain water use efficiency of Ya is much lower than that for Yw in the CRV. Although the rainfall in NVT fields and farmers' fields may be the same, better crop management in the NVT fields (e.g. timely operations and input use; proper drainage where necessary) favours crop growth and thus more efficient use of water. Hence, if nutrient and other crop management practices are improved to the level of the experimental plots, the water use efficiency could be approximately 3 to 6 times higher for maize, and 2 to 3 times higher for wheat depending on the HFZ. The Central lowland is characterised by lower actual yields but higher associated water use efficiency than the highlands, where water is less limiting. In the lowlands, any additional water results in a higher yield increase compared to the high rainfall areas.

Probably associated with financial and access problems (Adimassu et al., 2013), many farmers' fields did not receive mineral fertilisers. However, the yield difference between fields with and without mineral fertiliser input is very small and even negative in some HFZs. A first reason for this could be K or S limitation causing a poor response to N and P (Mengistu and Waktola, 2014; Astatky et al., 2004). Secondly, non-fertilized fields may have a higher intrinsic soil fertility than fertilized fields. Farmers' fertiliser allocation might have compensated this difference, leading to the apparent absence of a nutrient response. This hypothesis is supported by the significant ($P<0.001$) association between perceived soil erosion problems and fertiliser application, i.e. fields with perceived erosion problems received more fertiliser than fields without erosion. Soil erosion is a major cause of nutrient depletion (Haileslassie et al., 2005), leading to partial loss of the applied N and P, and some other nutrients (e.g. K), indicating a third reason for the small yield response to fertiliser. Therefore, information on erosion status should be utilized in nutrient recommendations and management. A fourth reason is that mineral N rates were far below the recommendation (Fig. 8), i.e. 10-40% (depending on HFZs) of the recommended rate for maize, and 35-45% for wheat, whereas the average P application is closer to the recommended rate (60-90%). For achieving current yield levels (Ya in Table 4) without further depleting soil nutrient stocks an application of at least 95-118 kg N ha^{-1} and 28-40 kg P ha^{-1} is needed assuming an average harvest index of 0.4 (Worku and Zelleke, 2007) and recovery fractions of 0.4 (N) and 0.17 (P) for maize and wheat. This application rate corresponds with the recommendation of (Molla, 2013) who estimated that 100-130 kg N ha^{-1} and 10-30 kg P ha^{-1} is needed for wheat production in the Central highlands of Ethiopia.

4.3 Data for yield and resource use analysis in Ethiopia

Within the Ethiopian agricultural research system an enormous amount of crop and variety data is collected annually from NVTs and demonstration plots across the country. The management of collected data, however, is poor, and is left in the hands of individuals, resulting in data loss and poor accessibility. In this study we were able to retrieve some of these data from different sources and we used it to assess yield gaps and benchmark agricultural production. The research system in Ethiopia, therefore: (1) needs to establish a database management system so that the available data can be exploited for various purposes, in addition to the purpose for which they were initially designed; and (2) should conduct non-nutrient-limited NVTs with more site-specific fertiliser rates so that yield truly represents Yw.

Despite its comprehensiveness, the CSA survey data suffered from changes in administrative (district and zonal) boundaries and inconsistencies in variable names across years, hampering automatic data queries and time-series analysis. In this study, we improved data consistency to enable time series analysis through spatial reassignment of farm data, and standardized variable names using the original CSA field books. Due to a lack of capacity or access problems, data in the region is underutilized (Coe and Stern, 2011). Therefore, with careful handling of aforementioned data-related limitations, the annual CSA survey data covering a range of crops and production areas can be used for similar analyses on other crops and agroecologies in Ethiopia.

We cannot rule out the possibility of errors related to data collection methods: (1) data on type and quantity of fertiliser were obtained through a survey; (2) farmers use local measurement tools/units to allocate fertilisers to small plots. The yield is normally measured by harvesting a quadrant by trained data collectors. Hence we expect that errors are larger for fertiliser than for yield data.

5. Conclusions and recommendations

There is an enormous yield gap and huge opportunity for yield increase through intensification and improved agronomic management in CRV. The scope for production increase is generally higher in the Eastern and Western highlands than in the Central lowlands. Because the current rates of fertilization are far below the recommendations, the potential to improve yields through higher fertiliser use seems obvious. However, the fact that our data reveal limited response to increasing nutrient application illustrates the importance of interacting management and environmental factors.

The experimental research data and the survey data can be used for yield gap and related farming system analysis. We recommend that the CSA includes some agronomically important variables such as planting and harvesting dates, more complete fertilization information, varieties and plant density and crop protection details for better-informed decision making.

While the potential for yield gap closure seems large in the CRV, future studies are required to explore the effects of different agronomic management options and their combinations on yield gap closure. Furthermore, enormous investments are required in human capacity, infrastructure and agricultural technology. In addition, land use change in CRV has already affected the basin water balance (Getnet et al., 2014), and therefore, the hydrological consequences of production increase through intensification need to be carefully analysed, and especially management options that combine high productivity and high water use efficiency need to be identified.

Acknowledgement

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Chapter 4

Narrowing crop yield gaps in Ethiopia: A model-based exploration of intensification options and trade-off with the water balance

This Chapter will be submitted as: Mezegebu Getnet, Katrien Descheemaeker, Martin van Ittersum, Huib Hengsdijk; Narrowing crop yield gaps in Ethiopia: A model-based exploration of intensification options and trade-off with the water balance.

Abstract

In the Central Rift Valley of Ethiopia (CRV), actual productivity of most cereals is less than 2 t ha^{-1} associated with low input use and poor crop management. After calibrating and validating the model based on experimental data, we used the Agricultural Production System Simulator (APSIM) to explore intensification options that enable to narrow prevailing yield gaps in the CRV and to analyse trade-offs with water losses through evapotranspiration. We set up a factorial simulation experiment [3 locations x 3 soils x 2 varieties x 3 residue removal levels x 2 planting densities x 6 nitrogen levels] for maize and wheat using 21 years of weather data to simulate yield and water balance components under current and future climate scenarios. We found that varietal selection and N fertilization are the most important factors contributing to yield gap closure, and that their effect depends on soil type and location. There is a trade-off between intensification and water losses through evapotranspiration: increasing the maize yield from 2 to 5 t ha^{-1} increased the transpiration by 45-91% in the highlands and 25-84% in the lowlands. Increasing wheat yield from 2 to 4 t ha^{-1} increased the transpiration by 100-160% in the highlands, and 75-150% in the lowlands. However, the trade-off can be minimized by choosing location-specific N levels at which both WUE and gross margin are maximised. These application rates varied between 75 and 250 kg N ha^{-1} across locations and soils, and allowed producing 80% of the water-limited yield (Yw) of maize and wheat. Climate change is projected to lower yield compared to current climate conditions as it decreases the maturity period, and it would result in decreased drainage and higher soil evaporation across all variety, location and management combinations for both crops. We recommend that promising intensification options at field scale are further analysed for their effect on the regional water balance.

Key words: Intensification, modelling, crop management, yield gap, trade-off, water balance

1. Introduction

In the recent past, increased food production in the Central Rift Valley (CRV) of Ethiopia was the result of an increase in the cultivated area (Meshesha et al., 2012; Biazin and Sterk, 2013). Agriculture expanded to marginal areas with low land productivity, mainly related to erosion and poor inherent fertility (Yimer and Abdelkadir, 2011). These land use changes affected the hydrological balance of the CRV, which is manifested through the declining water levels of the downstream lakes (Legesse et al., 2004; Getnet et al., 2014).

In the CRV, more than 70% of the area is already cultivated whereas most of the remaining land is unsuitable for agriculture. Therefore, future agricultural development should focus on increasing the productivity per unit area instead of expanding the agricultural area. However, the effects of agricultural intensification on the catchment hydrology should be taken into account to maintain ecosystem services that are already under pressure due to current agricultural land expansion (Getnet et al., 2014).

The current productivity of most cereals in the CRV is less than 2 t ha^{-1} and hardly grows, while the population increases with 2-3% per year (IFPRI, 2006; Admassu et al., 2013), underlining the challenge to feed the population from the currently cultivated land. However, there is potential for intensification in the CRV given the large yield gap between on the one hand current farmers' yields and on the other hand experimental and simulated yields (Kassie et al., 2014). This yield gap is mainly attributed to low input use and poor crop management, including inappropriate nutrient application, variety selection, planting (date and density), crop residue management and control of weeds, pests and diseases. Given the variation in available biophysical and socio-economic resources and conditions across the CRV, the yield gaps differ across crops, farming zones, soils and climate.

Improving input use and management can narrow yield gaps, but the lack of information on spatially explicit best bet combinations of input use and crop management options impede tailored and effective decision making towards yield gap closure. This is mainly because multi-factorial experimentation, taking into account Genetic x Environment x Management (G x E x M) interactions, is costly in terms of time and finances.

Improving crop management in an effort to narrow yield gaps influences the water balance of cropping systems at field scale (Eastham and Gregory, 2000). For example, intensification may result in a more efficient use of precipitation (Farahani et al., 1998; Badra et al., 2012), but may result in trade-offs of decreased downstream water availability due to low runoff and deep percolation. The impacts of intensification on the components of the water balance will differ by location, soil type, crop type and management and are poorly understood.

Agricultural system models are being used worldwide to explore options and solutions for enhanced food production and climate change adaptation. The Agricultural Production System Simulation (APSIM) model is one of the agricultural system models that has evolved over many years of research and has been applied to understand G x E x M effects on yield under current and changed climate scenarios (Probert et al., 1998; Asseng et al., 2002; Keating et al., 2003b; Holzworth et al., 2014).

In this paper, we explored a range of crop management options to narrow the prevailing yield gaps for maize and wheat at field scale in the CRV using the APSIM model. We exploited the capacity of APSIM to run a large number of simulations in a factorial setting to analyse the effects of many G x E x M combinations on crop productivity and the soil water balance. To address the trade-off between crop yield and water use, we identified fertiliser application rates that maximize water use efficiency and economic gross margins. To assess the possible effects of climate change all analyses were done for the present and future climate. With respect to future climate we focus on temperature change only as projections of precipitation changes for the study area are highly uncertain (Admassu et al., 2013; Kassie et al., 2013; Mekasha et al., 2014). We derived key lessons from the factor interactions and generate hypotheses about intensification scenarios that can be used in future research addressing the relationship between crop intensification and basin hydrology.

2. Materials and methods

2.1 Description of the study area

The study was conducted for the Central Rift Valley (CRV) of Ethiopia, approximately between 38°81' and 39°8' E, and 7°10' and 8°30' N. The CRV shows a remarkable diversity in altitude, temperature, rainfall and farming systems associated with differences in biophysical and socio-economic conditions. The diversity in conditions required to classify the CRV into three relatively homogenous farming zones (HFZs) i.e. Eastern highlands (EH), Central lowlands (CL) and Western highlands (WH) (Getnet et al. 2015, under review). The EH and WH are characterised by a higher altitude (about 3000 m a.s.l), higher rainfall (1600 mm yr^{-1}) and lower average temperature (16°C) compared with the CL at a lower altitude (1600 m a.s.l) and with lower rainfall (600 mm) and higher temperature (21°C). The CL located in between the EH and WH has a relatively flat topography compared with the mountainous relief in the two highlands. Luvisols, Nitosols, Andosols, Cambisols and Vertisols are the dominant soil types in the CRV. Of the dominant crops maize and wheat, late maturing varieties are predominantly cultivated in the EH and WH whereas early maturing varieties prevail in the CL. Crop production in CRV is mostly rainfed and the actual productivity is low due to the low input use and the poor crop management (Getnet et al. 2015).

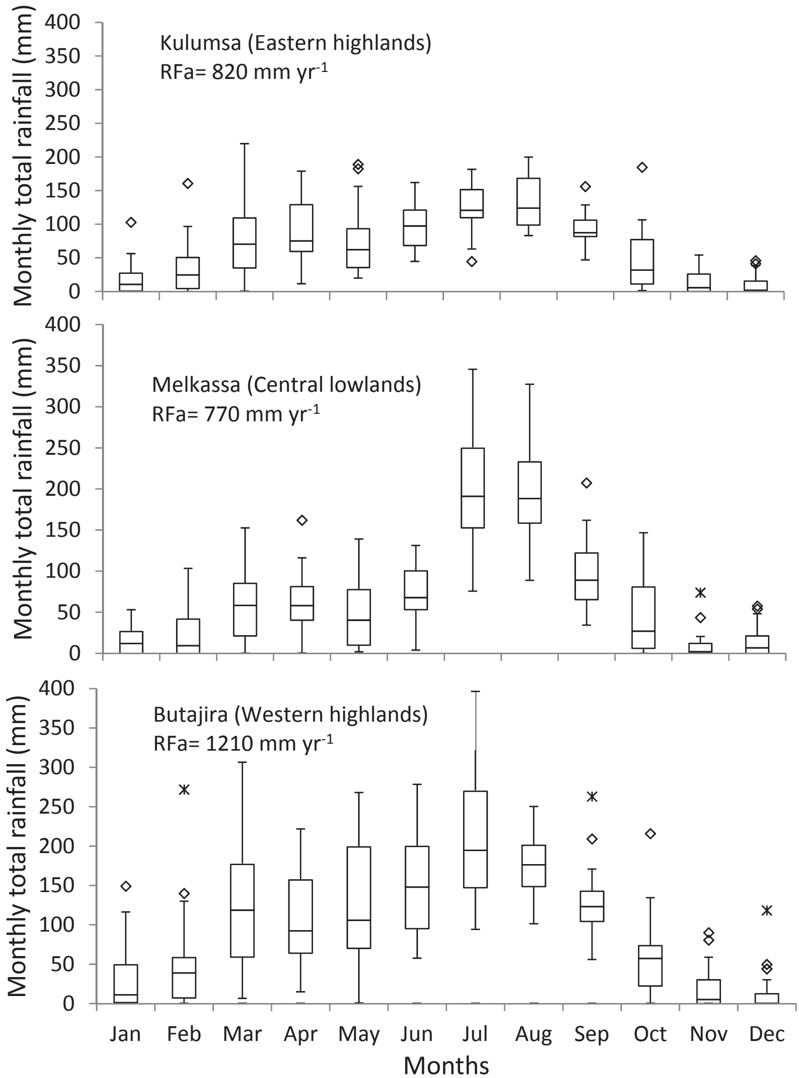

Figure 1. Distribution and variability of monthly rainfall at Kulumsa, Melkassa and Butajira (1989-2009); RFa= annual total rainfall.

2.2 Data

The minimum data to estimate water-limited crop yields (Yw) include data on daily weather, soil characteristics that determine root zone water holding capacity and runoff, and information of cropping systems including sowing dates, phenology, and optimum plant population density (Van Ittersum et al., 2013). The climate, soil, crop phenology and yield data used for APSIM model calibration and evaluation are described in Table 1.

Table 1. Description of the data used for calibration and evaluation of APSIM.

Data	Type	Location	Year	Scale/detail	Source
Current climate	Rainfall, Tmin, Tmax, Solar radiation	Galessa***, Meisso, Melkassa, Kulumsa, Butajira	21 yrs (1989-2009)	Daily	National Meteorology Agency and EIAR
Soil	Luvisols Andosols Vertisols	Galessa, Melkassa, Meisso		4-6 soil layers	EIAR soil profile descriptions, reports
Runoff	Luvisols Andosol Vertisols	Galessa: Melkassa: Meisso:	2007 2004 2004	Daily runoff from 2m x 2m runoff plots	Reports, database
Maize phenology and yield	Melkassa-1* BH660Q**	Melkassa, Kulumsa	2000, 2004, 2005 2002-2004, 2008	1.5 x 5 m; 3 replications	EIAR experimental data
Wheat phenology and yield	Hawi* Digelu**	Melkassa Kulumsa	2004, 2005, 2008 2005, 2007, 2008	3 x 3 m; 3 replications	EIAR experimental data

* Early maturing varieties; ** Late maturing varieties; *** is a location for which daily rainfall, Tmin and Tmax are available for 2 years and solar radiation data was obtained from the NASA power database; Data from Galessa and Meisso locations are used only for runoff calibration; Tmin= minimum temperature; Tmax= maximum temperature. EIAR = Ethiopian Institute of Agricultural Research

21-years climate record databases containing daily rainfall, minimum and maximum temperature, and solar radiation from three locations, were used for long-term simulations to represent the three homogeneous farming zones in the CRV, i.e. Kulumsa for the EH, Melkassa for the CL and Butajira for the WH.

APSIM-soil was parameterized for a Luvisol, Andosol and Vertisol based on measurements conducted at Galessa, Melkassa and Meisso, respectively by the Ethiopian Institute of Agricultural Research (EIAR) and (Kindu et al., 2008) (Annex I). These three soils are selected because observed runoff data was available for calibration of the fallow water balance, and the soils represent 60% of all soils in the CRV. The hydrological properties included soil bulk density, saturated water content, soil water at field capacity and wilting point. Where soil water at wilting point and field capacity were not directly available in soil descriptions, the parameters were estimated from other soil properties like texture and bulk density using pedotransfer functions (Chikowo et al., 2008). Other soil parameters such as soil albedo, diffusivity constant, rates of unsaturated and saturated flows were adopted from similar soils already described in APSIM.

Runoff data was obtained from previous studies on experimental runoff plots on bare Andosols (at Melkassa), and Vertisols (at Meisso) (Welderufael, 2006; Welderufael et al., 2009); and Luvisols (at Galessa, EIAR data).

Crop phenology and yield data (two maturity types for both maize and wheat) from Kulumsa and Melkassa research centres of EIAR were used to calibrate the APSIM-maize and APSIM-wheat models. Kulumsa is representative for the EH and WH, whereas Melkassa for the CL. The crop data originated from the rainfed National Variety Trials (NVTs), in which weeds were controlled by intensive and timely hand weeding, and diseases and pests were controlled by spraying pesticides. The NVTs received locally recommended N and P fertiliser rates (Getnet et. al. 2015). Maize was sown at a density of 5.3 plants m^{-2} for early maturing varieties at Melkassa and 5.6 m^{-2} for late maturing varieties at Kulumsa whereas both wheat varieties were sown at a density of 320 plants m^{-2} in both Melkassa and Kulumsa.

2.3 Description of the APSIM model

APSIM is a software tool that enables to simulate G x E x M interactions (McCown et al., 1996; Keating et al., 2003a). The central position in the model is taken by the soil rather than the crop where changes in the soil state variables are simulated continuously in response to weather, crop growth and management (McCown et al., 1995; McCown et al., 1996; Probert et al., 1998). APSIM provides a flexible structure to simulate effects of climate and soil management on crop growth and yield based on several integrated simulation modules (Keating et al., 2003a). In this study emphasis is on the water balance, crop (maize and wheat), nutrient (N), and management (planting density, maturity type, sowing rules, residue removal) modules.

***APSIM-SoilWat* module**

A reliable estimation of the soil water balance is required for an accurate estimation of crop growth and yield as well as hydrology. The APSIM SoilWat module is a cascading water balance model (Asseng et al., 1998) that specifies the water characteristics of the soil mainly in terms of soil bulk density, saturated water content (SAT), drained upper limit (DUL), and lower limit (LL) (Probert et al., 1998).

Runoff, drainage, soil evaporation, transpiration, unsaturated flow and solute flux/flow are the main soil water processes in the APSIM-SoilWat module (Verburg, 1995). In APSIM-SoilWat, runoff is estimated using the USDA-SCS curve number (CN) approach that includes effects of soil water content, crop height, and soil cover both from crop and crop residues (USDA-NRCS, 2004). The user supplies the CN for average antecedent rainfall condition (CN) that is used to calculate the wet (high runoff potential) and the dry (low runoff potential) curves. The SoilWat module uses the family of curves between these extremes to calculate runoff depending on the daily soil moisture content. Furthermore, the CN is progressively reduced in response to the development of crop cover and crop height up to a certain threshold above which there is no effect.

APSIM-maize and wheat

The APSIM maize and wheat modules simulate crop growth and development with a daily time step based on the accumulation of thermal time. Maize and wheat growth responds to climate, i.e. temperature, rainfall and radiation (from the input module), soil water supply (from the SoilWat module) and soil nitrogen (from the soilN module). The maize and wheat modules provide information on crop cover to the SoilWat module for calculation of evaporation rates and runoff.

2.4 Model calibration

APSIM-SoilWat, APSIM maize and APSIM wheat were calibrated before they were used for simulation of the different G x E x M options.

2.4.1 Calibration of the APSIM-SoilWat module

APSIM-Soil was parameterized for three soil types (Annex 1). The U and CONA were set at 6 mm day^{-1} and 3.5 mm day^{-1}, respectively (Chikowo et al., 2008).

We calibrated the bare soil runoff curve number for each soil type by comparing simulated with observed daily runoff from one year of measurements using R^2, the Root Mean Square Error (RMSE) and model efficiency (ME) as indicators for model performance.

$$RMSE = \left[\left(\frac{1}{\mathrm{n}}\right)\sum_{i=1}^{n}(Oi - Si)^2\right]^{\frac{1}{2}}$$

$$ME = 1 - \frac{\sum_{i=1}^{n}(Oi - Si)^2}{\sum_{i=1}^{n}(Oi - \bar{O})^2}$$

where Oi and Si are observed and simulated values of the i^{th} event respectively, and $\bar{O}$ is the mean of observed values. The model reproduces observed data best when ME is close to 1 and RMSE has a low value. Due to lack of data model evaluation was limited to only one year for each soil type.

2.4.2 Calibration of APSIM-Crop modules

The crop phenology and yield data from experimental NVTs at Melkassa and Kulumsa are used for the calibration and evaluation of APSIM maize and APSIM wheat.

We conducted the model calibration based on data from one year for one early maturing and one late maturing variety of each crop. First, we adjusted the thermal time from planting to flowering until the flowering days were reasonably estimated. Then, we adjusted the thermal time between flowering and maturity until the simulated maturity dates matched observed dates. Finally, to adjust yield, we fine-tuned the thermal time between start of grain filling and maturity and the grain growth rate during grain filling. Due to lack of data we did not account for differences in phenology due to photoperiod and vernalisation. Depending on the availability of experimental data on phenology and yield, two or three years with data of the two maize varieties and the two wheat varieties were used for model evaluation.

2.5 Simulation

APSIM was configured to simulate the effect of various combinations of G x E x M factors and levels, including crop and cultivar (G), location-specific weather and soils (E), and planting density, crop residue management and N application (M) (Table 2). A factorial simulation was setup for each of the three locations, i.e., EH, CL and WH; and two crops, i.e. maize and wheat. For each location-crop combination, the simulation comprised all possible combinations of two varieties (early and late maturity types), six N levels, two plant densities, three crop residue management levels, two soil types and two climate scenarios totalling 36,288 simulation-years each on a daily basis (Table 2).

Table 2. Factorial combinations of maize and wheat input and management options: factors and the levels within each factor.

Factors	Number of levels per crop	Levels
Nitrogen application (kg ha^{-1})	6	20*, 75, 125, 175, 250, 350
Plant density (plants m^{-2})	2	5.3 and 6.6 for maize; 250 and 320 for wheat
Crop residue management	3	0%, 50%, 100% crop residue removed after harvest
Maturity type	2	Early maturing (Melkassa-1 for maize, Hawi for wheat), late maturing (BH660 for maize and Digelu for wheat)
Soils	2	Lv and Vr (EH); Ad and Lv (CL); Lv and Vr (WH)
Climate scenario	2	Current (1989-2009) and mid-century (2050)
Locations	3	EH (Kulumsa), CL(Melkassa), WH (Butajira)

* This rate represents farmers' current average N application based on Getnet et al. (2015); Lv = Luvisols, Vr = Vertisols, Ad= Andosols; EH= Eastern highlands, CL= Central lowlands, WH= Western highlands

The soil organic matter and soil nitrogen contents were reset annually in the simulation at planting to avoid the confounding effect of long-term dynamics of organic carbon associated with residue cover management.

The climate scenarios represent current (1989-2009) and future climate by mid-century. We selected the worst case scenario from the range of changes in minimum (+3.2 °C) and maximum temperature (+3.5 °C) for the CRV, obtained from three General Circulation Models (GCMs), run under the Representative Concentration Pathways RCP8.5 of 571 ppm of CO_2 (Kassie et al., 2015). Changes in minimum and maximum daily temperatures were implemented by adding the temperature change to the historical values (Webb and Stokes, 2012).

In our crop simulation using future climate, we elevated the CO_2 concentration for wheat to the RCP8.5 level of 571 ppm. We maintained the current CO_2

concentration of 350 ppm for maize because maize is saturated at that concentration and no effect on maize yield was expected from an elevated CO_2 concentration (Leakey et al., 2006).

APSIM outputs for further analysis included dry grain yield and annual values for runoff, drainage, soil evaporation and crop transpiration for all G x E x M combinations. In order to investigate the trade-off between crop yield and irrecoverable water losses through evapotranspiration, we calculated the water use efficiency (WUE) as the kg of grain yield per mm of water lost by evapotranspiration per year. Gross margins associated with increasing N rates were calculated based on fertiliser costs and benefits from grain yield. We used the farmers' purchasing price of urea in 2012 (IFPRI, 2013), which was converted to a price per kg of N, and the average selling price of maize and wheat for the period of 2006-2011 (FAO, 2013). Optimal N application rates were identified for specific variety x location x soil conditions based on maximum WUE and gross margin.

3. Results

3.1 Model evaluation

The best estimate of bare-soil runoff (highest R^2, lowest RMSE and ME closest to 1) was obtained at a runoff curve number for average antecedent moisture condition of 78 for Andosols (RMSE = 4.7 mm day^{-1}; ME=0.85), 82 for Luvisols (RMSE=1.6 mm day^{-1}; ME=0.47), and 88 for Vertisols (RMSE=1.5 mm day^{-1}; ME=90) (Fig. 2).

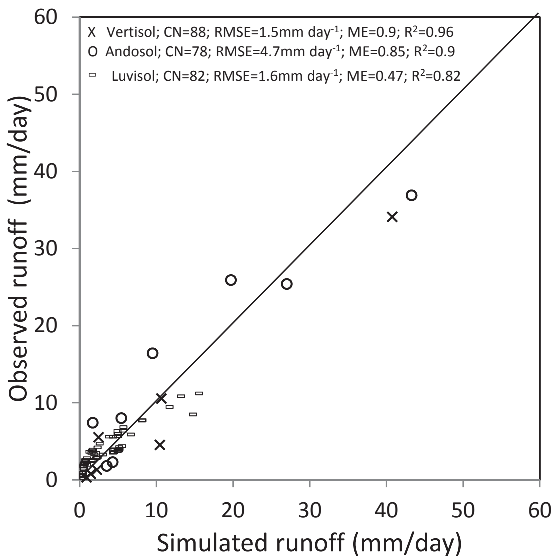

Figure 2. APSIM simulated and observed daily runoff from a bare soil for three major soil types (representative for ca. 70% of the agricultural land) in the Central Rift Valley.

Observed and simulated phenology and yield data used for model calibration and validation are presented in Table 3. Observed maturity days ranged from 108-116 days after sowing (DAS) for early maturing maize (Melkassa-1), and 182-237 DAS for late maturing maize (BH660). The maturity days ranged from 88-93 DAS for early maturing wheat (Hawi), and 129-148 DAS for late maturing wheat (Digelu) across years and varieties planted in the two locations Melkassa and Kulumsa. Given the high variability across years in observed flowering dates, maturity dates and yield of all varieties of maize and wheat, the model evaluation suggests a reasonably close estimation of the observed phenology and yield (Table 3).

Table 3. Observed and simulated phenology and yield of early and late maturing varieties of maize and wheat grown in the Central Rift Valley.

Crop	Model phase	Cultivar	Year	Planting date	Grain yield* ($t\ ha^{-1}$)		Days from planting to flowering (days)		Days from planting to maturity (days)	
					Obs.	Sim.	Obs	Sim.	Obs.	Sim
Maize	Calibration	Melkassa-1	2004	19-Jun	5.32	5.34	57	57	114	113
		BH660	2002	15-Apr	7.39	7.36	99	99	186	188
	Evaluation	Melkassa-1	2000	20-Jun	4.67	5.03	54	57	108	116
			2005	23-Jun	5.65	5.34	53	54	116	111
		BH660	2003	30-May	8.80	7.16	95	112	195	204
			2004	29-May	6.80	6.80	116	110	182	206
			2008	16-Apr	6.72	7.11	113	119	237	225
Wheat	Calibration	Hawi	2008	14-Jul	3.08	3.09	50	51	88	88
		Digelu	2008	22-jun	4.62	4.50	80	81	148	146
	Evaluation	Hawi	2004	25-Jun	2.90	2.92	49	51	89	86
			2007	13-Jul	2.08	2.68	50	51	93	87
		Digelu	2005	25-Jun	4.09	4.39	74	73	130	131
			2007	30-Jun	4.05	4.45	69	75	129	136

* Grain yield was at 12.5% moisture content; Obs.= observed, Sim. = simulated; Melkassa-1 and Hawi are early maturing maize and wheat varieties, respectively, from experiments at Melkassa (1550 m a.s.l). BH660 and Digelu are late maturing varieties of maize and wheat, respectively, from experiments at Kulumsa (2200 m a.s.l).

3.2 Yields and yield responses

There was a substantial variation in maize yield and response to N across HFZs (Fig. 3a). Maize yields were higher in EH and WH than in the CL. Average grain yield was 7.3 t ha^{-1} in EH, 5.7 t ha^{-1} in CL and 7.1 t ha^{-1} in WH (average across all management options, varieties and years). Maize yields also differed between varieties, i.e. 5.2 t ha^{-1} and 8.2 t ha^{-1} for early and later maturing varieties, respectively (across management, locations and years). Varietal selection can give a maize yield advantage of ca. 0.6-1.9 t ha^{-1} at a low N-rate (20 kg N ha^{-1}) across HFZs. The yield advantage of the late maturing variety was higher at high N rates, i.e. 2-8 t ha^{-1} (across locations, soils, planting densities and crop residue levels).

Yield response levelled off at lower N rates for the early maturing maize variety than for the late maturing variety. Yields of the early maturing maize ranged from 1.1 t ha^{-1} at 20 kg N ha^{-1} to a maximum of ca. 6 t ha^{-1} at 125 kg N ha^{-1}, with similar response across HFZs, soils and plant densities (Fig. 3a). For the late maturing variety of maize, the yield response to N varied strongly across HFZs.

Yields ranged from ca. 2 t ha^{-1} at 20 kg N ha^{-1}, to ca. 13 t ha^{-1} at 350 kg N ha^{-1} in Luvisols of the EH and WH, and Vertisols of the WH. The yield levelled off at ca. 8 t ha^{-1} (at 175 kg N ha^{-1}) on Luvisols, and at ca. 6 t ha^{-1} (125 kg N ha^{-1}) on Andosols of the CL.

Differences in yield response between soils within the same HFZs were small, but on Vertisols of the EH maize yield declined with N rates beyond 175 kg ha^{-1} (Fig. 3a). On the contrary, on the same soils in the wetter WH, a strong yield response was observed at higher N rates. The interaction effect between HFZ and soil on yield response can thus be explained by climatic differences.

Grain yield was slightly higher at higher planting density for both maize and wheat across all HFZs, varieties and soils. The difference was higher for maize (ca. 0.5 t ha^{-1}) than for wheat (ca. 0.1 t ha^{-1}).

When 100% of the crop residues from the previous harvest were retained on Vertisols of the EH, the maize yield continued to increase up to ca. 14 t ha^{-1} at an N rate of 250 kg ha^{-1}, after which it levelled off (data not shown). There was a small increase in yield with an increase in residue retention on Luvisols of the EH, and Andosols and Luvisols of the CL (up to 0.5-2 t ha^{-1} at 250 N ha^{-1}). Residue retention had hardly any effect on yield on both soils of the high rainfall WH.

For wheat, the maximum yield and the response to N were highest in EH and lowest in CL (Fig. 3b). Average grain yield was 5.5 t ha^{-1} in EH, 4.0 t ha^{-1} in CL and 4.5 t ha^{-1} in WH (average of all management options, varieties and years). Contrary to maize the difference between the early and late wheat variety was only small, 4.6 vs. 5.0 t ha^{-1}.

Nitrogen fertilization increased wheat yields from less than 2 t ha^{-1} at 20 kg N ha^{-1} to ca. 8 t ha^{-1} in the EH and WH, and ca. 5 t ha^{-1} in the lowlands (Fig. 3b). Yields levelled off at N rates of 250 kg ha^{-1} for both varieties across all HFZs and soils. The difference between varieties in yield response to N was generally small. Residue retention at harvest did not affect wheat yield.

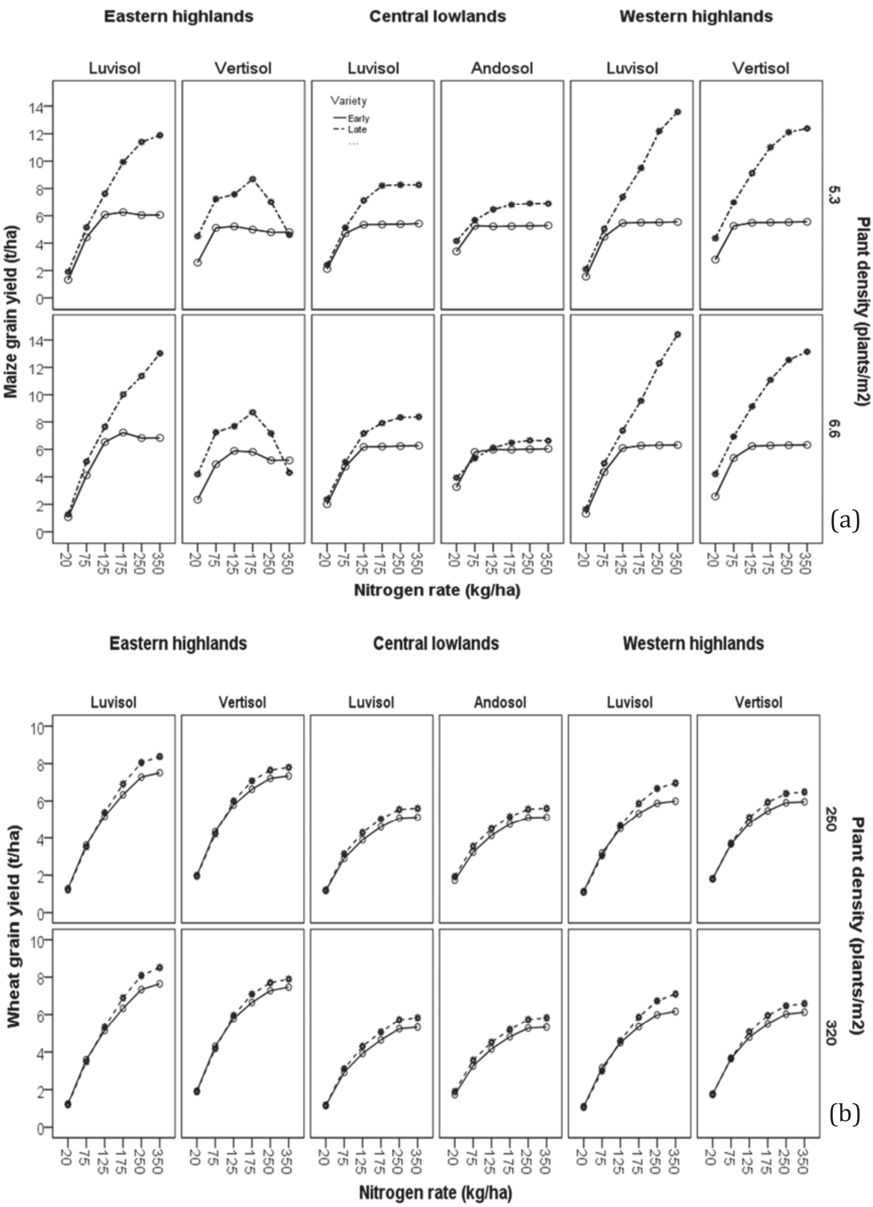

Figure 3. Simulated response of early and late maturing varieties of (a) maize and (b) wheat grain yield to nitrogen fertilization in major soils of the Eastern highlands, Central lowlands and Western highlands for two plant densities at 100% crop residue removal for current climate (1989-2009).

3.3 Yield variability under current and future climate

Generally, yield variability was larger for maize than for wheat (Fig. 4). Yield variability was lower at low N input than at high N input for both crops and varieties across the major soils in all HFZs (Fig. 4a,b). The variability was often larger for the late maturing variety than for the early maturing variety, while it was extremely large for high N input, late maturing maize on Vertisols in the EH, and Andosols and Luvisols in the CL. In the latter situations, the cultivation of the late maturing maize at high N input was associated with a risk of low yields and sometimes crop failure and thus the risk of losing investments in fertiliser. For example, at high N rate on Vertisols of the EH at least a quarter of the years produced less than what could be produced at low N rate (see the lower quartiles and lower values of the whisker plot in Fig. 4a). Harvest failures of maize occurred more frequently on Vertisols in the EH than on other soils: three years with a complete failure and four years with very low yields out of the 21 simulation years were found on Vertisols, while over the same period no crop failures were simulated for Luvisols in the same HFZ.

For wheat, though variability was relatively small, there were more extreme (low) outliers in the CL than in EH and WH. Similarly to maize, wheat at high N input showed larger yield variability than wheat at low N input.

Climate change reduced yield of both maize and wheat at high N, but not or hardly at low N. On average (across HFZs, soils and varieties), maize and wheat grain yields decreased due to climate change by ca. 1.1 t ha^{-1} and 0.9 t ha^{-1}, respectively, at an N rate of 175 kg ha^{-1} compared with 0.2 t ha^{-1} and 0.03 t ha^{-1} at an N rate of 20 kg ha^{-1}. Early maturing varieties of both crops seemed more robust to climate change with smaller yield reductions compared to late maturing varieties (Fig. 4a,b). For maize, the impact of climate change was more pronounced in the already risky HFZ-soil combinations, i.e. on Vertisols in the EH and Andosols in the CL. For wheat, the impact of climate change was consistent across HFZs and soils, with a larger variability for the late maturing variety and the higher N rate.

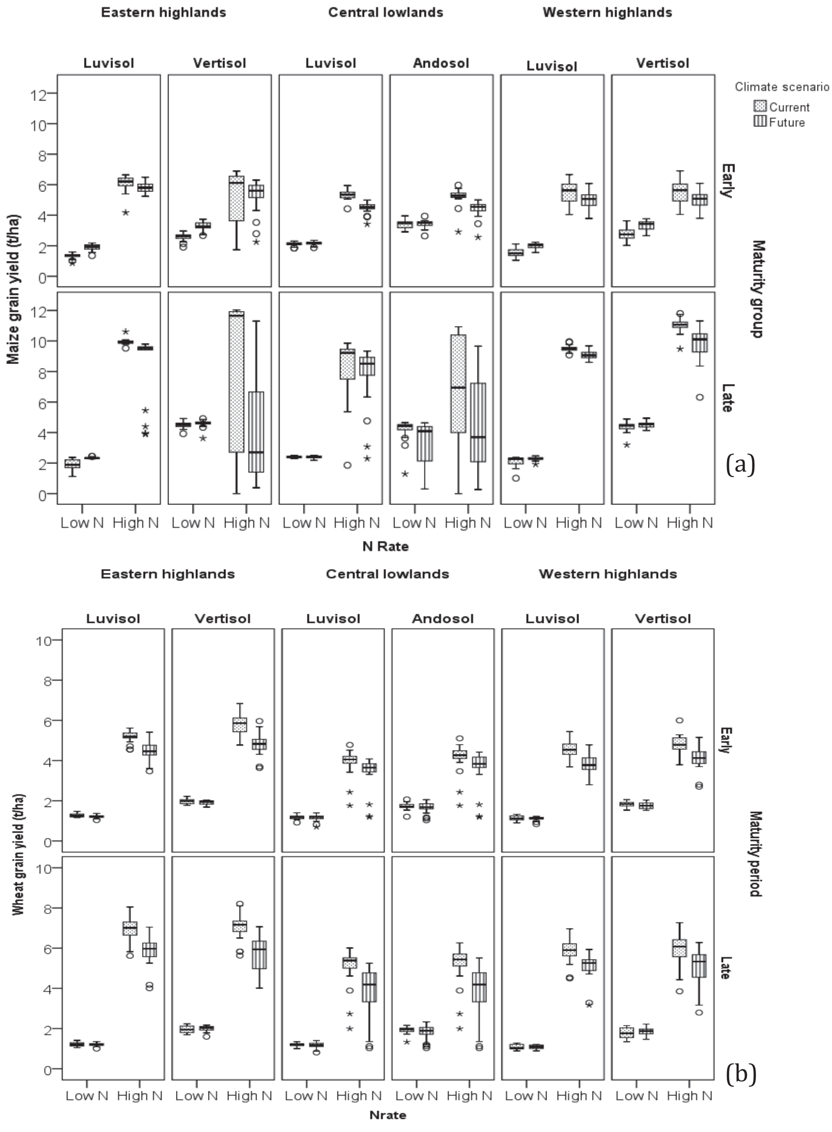

Figure 4. Variability of (a) maize and (b) wheat grain yield under current (1989-2009); and future (2050s) climate scenarios in major soils across HFZs of the CRV at 100% crop residue removal; plant density of 5.4 plants m^{-2} for maize and 250 plants m^{-2} for wheat; the low N rate is the average farmers' rate of 20 kg N ha^{-1}; the high N rate is 125 kg ha^{-1} for early and 175 kg ha^{-1} for late maturing varieties.

3.4 Water balance

3.4.1 General effects of G x E x M combinations

The relative importance of water balance components varied with HFZs, percent of crop residue removed, and soils (Fig. 5). Vertisols, for example, generated more runoff than Luvisols in the same HFZ. The annual soil evaporation and crop transpiration were the largest terms in the water balance on maize land (Fig. 5a). The share of soil evaporation in the water balance was 33-51% on Luvisols, 49-52% on Andosols and 33-58% on Vertisols. The share of crop transpiration was 21-28% on Luvisols, ca. 23% on Andosols and 23-30% on Vertisols.

On wheat fields, drainage, soil evaporation and transpiration were the largest terms. Less runoff and more drainage was observed for wheat compared with maize (Fig. 5). Runoff from wheat fields contributed less than 10% to the annual water balance.

3.4.2 Plant density and crop residue management

As the effects of residue removal on the water balance were the same for both plant densities only results for the low plant density are shown (Fig. 5). Runoff and soil evaporation increased, whereas drainage decreased with an increasing percentage of maize crop residue removal across HFZs and soils (Fig. 5a). Crop residue removal had no effect on the water balance of wheat (Fig. 5b).

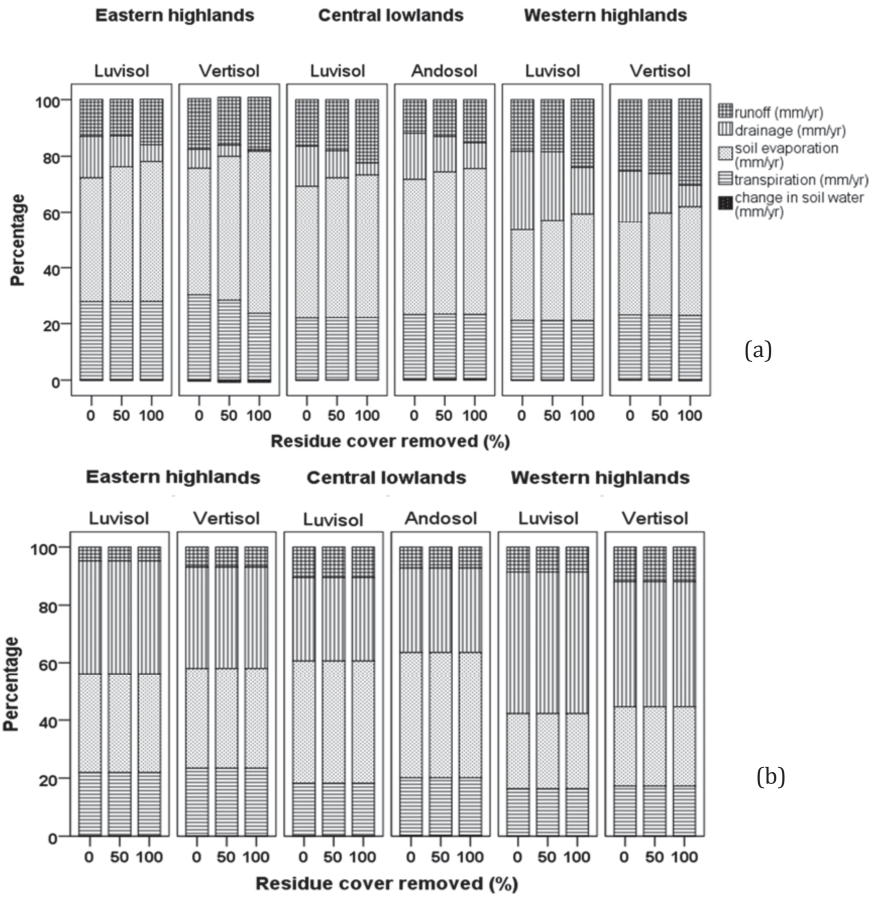

Figure 5. Effect of residue removal on the components of the annual water balance on (a) maize, and (b) wheat fields across HFZs and major soils of the CRV. Data are from the early maturing variety for the Central lowlands at 125 kg N ha^{-1} and for the late maturing varieties for the Eastern and Western highlands, at 175 kg N ha^{-1}, and based on low plant densities.

3.4.3 Nitrogen fertilization

In both crops, nitrogen fertilization increased transpiration, which was associated with a decrease in drainage in maize (Fig. 6a), and a decrease in soil evaporation in wheat (Fig. 6b).

Increasing the N application rate from the current farmers' practice (20 kg N ha^{-1}) to 75 kg N ha^{-1} in maize increased the transpiration by 45-91% in the highlands and 25-84% in the lowlands. The increase in transpiration was associated with a decrease in drainage of 25-60% in EH and WH, and 40-80% in the CL (ranges across locations, soils, varieties and plant density levels).

For wheat, the same increase in the N application rate (from 20 to 75 kg N ha^{-1}) resulted in increased transpiration by 100-160% in EH and WH, and 75-150% in the CL (Fig. 5b). Drainage increased by 30-50% in EH and WH, and 8-30% in the CL, while runoff decreased by 27-50% in EH and WH, and 22-33% in CL (Fig. 5b). Wheat at lowest N rate (20 kg N ha^{-1}) produced more runoff than at the higher N rates.

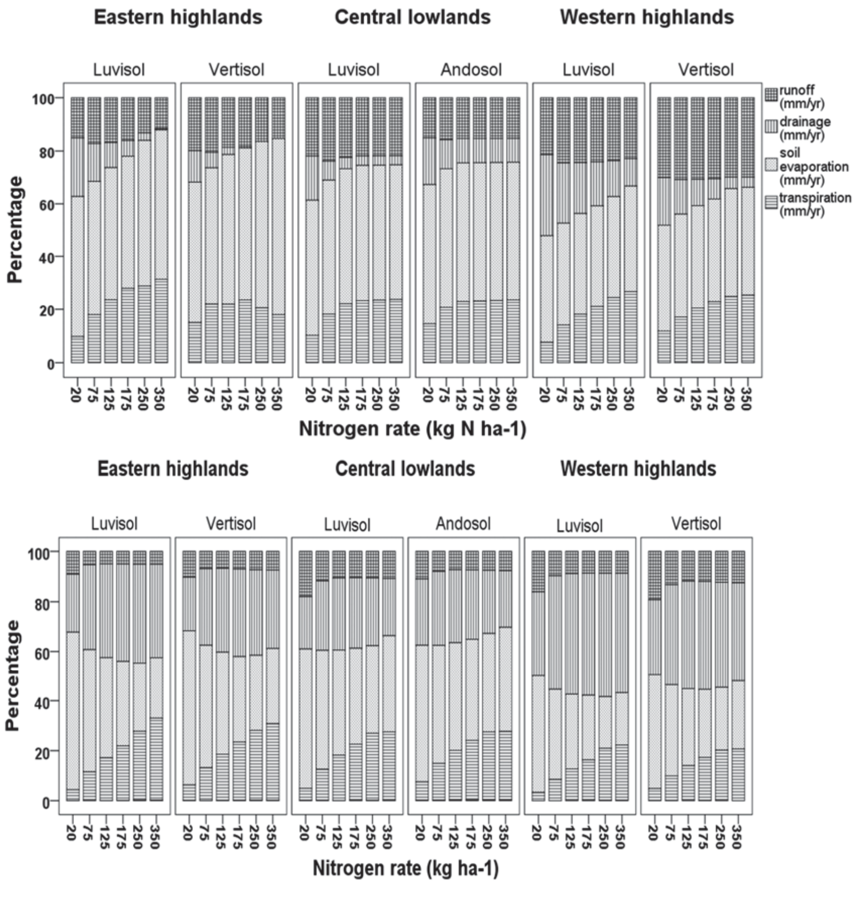

Figure 6. Effect of nitrogen fertilization on the components of the annual water balance on (a) maize, and (b) wheat fields across HFZs and major soils of the CRV. Data are from the early maturing variety for the Central lowlands and from the late maturing varieties for the Eastern and Western highlands at 100% crop residue removal; plant density of 5.3 plants m^{-2} for maize and 250 plants m^{-2} for wheat.

3.4.5 Climate change

Climate change caused a decrease in drainage (10-50%) and an increase in soil evaporation (6-20%) across all G x E x M combinations for both crops (Table 4). The magnitude of change varied across HFZs, crops and N levels. For example, the decrease in drainage was greater in the highlands (up to 80 mm yr^{-1} for maize and up to 115 mm yr^{-1} for wheat) than in the lowlands (Table 4). Transpiration slightly increased with climate change at low N rates (1-18%), and decreased at high N rates (0.5-15%).

Table 4. The impacts of climate change on the components of the water balance across HFZs, soils, varieties and N levels of maize and wheat.

HFZ	Soil	N rate	Maize: Change in runoff (mm yr^{-1}) Early	Late	Maize: Change in drainage (mm yr^{-1}) Early	Late	Maize: Change in soil evaporation (mm yr^{-1}) Early	Late	Maize: Change in transpiration (mm yr^{-1}) Early	Late	Wheat: Change in runoff (mm yr^{-1}) Early	Late	Wheat: Change in drainage (mm yr^{-1}) Early	Late	Wheat: Change in soil evaporation (mm yr^{-1}) Early	Late	Wheat: Change in transpiration (mm yr^{-1}) Early	Late
Eastern highlands	Luvisol	20	1	0	-23	-45	17	30	6	15	12	13	-37	-47	24	32	1	2
		75	2	-4	-28	-52	19	35	6	23	1	1	-43	-46	43	42	0	3
		125	2	-12	-22	-45	19	40	1	21	-1	-1	-48	-48	48	43	1	6
		175	5	-23	-11	-33	10	66	-12	1	-1	-2	-49	-48	48	41	3	9
		250	12	-12	-4	-22	4	18	-21	14	0	0	-48	-49	44	38	4	11
		350	12	-36	-4	-4	4	62	-21	-23	4	2	-79	-69	91	87	-15	-20
	Vertisol	20	-5	-2	-22	-49	19	33	7	19	5	7	-34	-43	24	31	4	5
		75	-5	-15	-18	-36	14	62	5	-6	2	3	-42	-51	37	42	3	6
		125	-4	-32	-11	-23	11	77	2	-26	-3	-2	-47	-49	44	41	5	10
		175	4	-34	-1	-5	1	75	-5	-40	-3	-2	-57	-62	56	61	4	3
		250	9	-18	-1	0	-7	31	-3	-16	-1	0	-68	-75	66	88	3	-12
		350	9	-9	-1	0	-8	1	-2	6	-1	0	-109	-88	130	119	-19	-31
Central lowlands	Luvisol	20	3	-6	-34	-54	23	45	6	18	3	3	-18		12	13	2	3
		75	-8	-31	-22	-20	25	46	4	11	7	12	-27	-31	17	22	3	-3
		125	-4	-7	-11	0	24	16	-11	-9	8	16	-34	-37	29	38	-2	-16
		175	1	-10	-6	0	23	17	-19	-8	8	18	-38	-41	39	60	-8	-37
		250	1	-6	-7	0	23	11	-18	-9	12	20	-55	-50	81	93	-37	-63
		350	1	-3	-7	0	23	7	-18	-7	16	22	-37	-37	63	83	-42	-67
	Andosol	20	-3	-12	-33	-38	26	48	7	2	-1	0	-17	-18	11	12	6	5
		75	-7	-12	-15	-19	27	48	-6	-19	3	7	-24	-28	18	24	3	-4
		125	-3	-9	-3	-9	26	46	-20	-28	5	11	-31	-34	29	43	-3	-20
		175	-3	-8	-4	-4	26	45	-21	-33	5	12	-36	-34	45	66	-14	-44
		250	-3	-8	-4	-3	26	45	-20	-34	7	12	-29	-25	63	77	-40	-64
		350	-3	-8	-4	-3	26	45	-20	-34	6	12	-13	-12	48	67	-42	-67
Western highlands	Luvisol	20	2	5	-47	-71	38	51	7	15	9	10	-41	-46	29	32	3	5
		75	-2	1	-44	-79	39	57	7	22	7	5	-49	-55	37	41	6	9
		125	-1	-2	-33	-76	39	60	-4	22	3	-1	-46	-45	35	33	7	14
		175	2	-3	-20	-73	39	60	-18	18	7	4	-53	-47	42	25	4	18
		250	3	-2	-18	-57	38	58	-21	2	10	6	-78	-69	77	66	-9	-3
		350	3	5	-18	-22	38	36	-21	-19	17	11	-114	-94	121	96	-24	-12
	Vertisol	20	-12	-13	-35	-60	39	55	9	20	3	10	-36	-52	26	32	7	9
		75	-8	-7	-33	-73	40	59	4	22	13	15	-56	-68	34	39	9	14
		125	-7	-9	-16	-70	39	60	-15	19	15	11	-69	-61	48	34	7	17
		175	-7	-9	-11	-56	39	59	-21	7	11	11	-67	-68	51	49	6	7
		250	-6	-7	-10	-27	39	51	-21	-17	22	19	-108	-94	105	93	-18	-17
		350	-6	-7	-11	-21	39	51	-21	-22	32	26	-103	-90	99	85	-27	-22

3.5 Economic analysis

The largest increase in gross margins was obtained by increasing the N application rate from 20 to 75 kg N ha^{-1}. For both wheat varieties, gross margins increased further with increasing N input up to 250 kg ha^{-1} across all locations and soils (Table 5 and 6). For maize, the optimum N application rate was lower for the early maturing variety at 75-125 kg ha^{-1} than for the later maturing variety at 175-250 kg ha^{-1} depending on the location (Table 5 and 6).

Table 5. Fertiliser costs incurred and gross margins for early and late maturing varieties of maize and wheat at different N rates on a per hectare basis. Gross margin was calculated as the product of grain product and price, minus cost of N; bold numbers are the highest gross margins.

	N rate (kg ha^{-1})	Cost (USD) of N	Gross margin (USD)			
			Maize		Wheat	
			Early	Late	Early	Late
Eastern highlands (Luvisols)	20	28	256	379	417	397
	75	105	840	997	1158	1121
	125	174	**1125**	1456	1630	1701
	175	244	1095	1884	1966	2165
	250	348	945	**2090**	**2191**	**2460**
	350	488	808	2056	2133	2436
Central lowlands (Andosols)	20	28	698	861	577	643
	75	105	**1020**	1109	1023	1133
	125	174	943	1207	1266	1393
	175	244	876	**1214**	1411	1551
	250	348	777	1128	**1430**	**1591**
	350	488	644	986	1298	1467
Western highlands (Vertisols)	20	28	570	905	603	601
	75	105	**1020**	1389	1175	1186
	125	174	1000	1778	1499	1608
	175	244	934	2114	1664	1826
	250	348	834	**2244**	**1712**	**1884**
	350	488	700	2163	1590	1775

3.6 Water use efficiency

The water use efficiency (WUE) varied with crops, varieties, locations, soils and management such as plant density and crop residue removal. Table 6 provides an overview of the WUE variation with N application and variety for selected soils in each of the HFZs. The maximum WUE of maize was 9-16 kg grain ha^{-1} mm^{-1} on Luvisols in the EH (higher value for the late variety), 9-10 kg grain ha^{-1} mm^{-1} on

Andosols in the CL, and 8-15 kg grain ha^{-1} mm^{-1} on Vertisols in the WH. The maximum WUE was attained at N rates of 125, 75 and 75 kg ha^{-1} in EH (Luvisols), CL (Andosols) and WH (Vertisols), respectively, for the early maturing variety and at N rates of 250, 250 and 350 kg N ha^{-1} for the late maturing variety in those HFZs and soils.

For wheat, WUE hardly differed between the two varieties, i.e. 17-18 kg grain ha^{-1} mm^{-1} in the EH, 9-10 kg grain ha^{-1} mm^{-1} in the CL, and 11-12 kg grain ha^{-1} mm^{-1} in the WH, with the higher value for the late maturing variety. Maximum WUEs were attained at 250 kg N ha^{-1} across the three HFZs and both varieties.

4. Discussion

4.1 Yields and water balance

Simulated yields of maize and wheat varied with location, soils, N input level and management. Yields were higher in EH and WH and lowest in CL as a result of the higher seasonal rainfall and earlier onset of rainfall in the highlands compared with the CL. This trend matches the differences in actual and experimental yields across the three HFZs (Getnet et al., 2015). In addition to the climatic and soil factors related to location, variety selection and nitrogen input had the strongest impact on maize yield. Yields of the late maturing varieties were higher than of the early maturing varieties particularly in the highlands of the CRV, because the growing period in the highlands is long enough to accommodate the maturity period of the late maturing varieties. To fully benefit from the longer growing periods in the highlands higher N rates are needed than in the CL. However, decisions related to N input should be made with care as the yield response varied across locations, soil types and varieties. For example, a high N rate (>175 kg N ha^{-1}) resulted in severe yield reduction for the later maturing maize growing on Vertisols of the EH (Fig. 3a), associated with water stress shortly before the start of grain filling period (data not shown). Also, high year-to-year variability and frequent crop failures in maize on Vertisols (Fig. 4a) illustrated the riskiness of high-input cultivation in these conditions. In contrast with maize, high-input wheat production was fairly resilient to climate variability, particularly under current climate conditions (Fig. 4b). This could be because runoff from wheat fields was lower (Fig. 5), potentially resulting in higher water availability and less drought stress compared to maize.

Our simulation results indicated a small positive effect of residue retention on maize yield. Crop residue retention increases the soil infiltration capacity (Woyessa and Bennie, 2007), water availability and yield (Wilhelm et al., 2004), and rain water use efficiency (Zeleke et al., 2004). However, farmers in the CRV prefer to use crop residues for feeding livestock during the dry period and therefore usually harvest these residues. The effect of crop residue management on runoff was weaker in wheat than in maize, which could be related to the larger residue production of maize (10-12 t ha^{-1} compared to 3-4 t ha^{-1} for wheat) and the low runoff in wheat anyway. Another reason could be related to the higher decomposition rate of wheat straw compared with maize (Broder and Wagner, 1988), resulting in less residue cover protecting the soil surface.

Varietal differences were smaller for wheat than for maize, which could be due to several factors. First, the genetic characteristics of the varieties that are currently used in the CRV are not well known. We, therefore, did not specify some wheat variety specific parameters (vernalisation sensitivity and photo period sensitivity) to avoid misleading assumptions. Second, detailed analyses of the simulations showed that the late maturing wheat variety produced more vegetative biomass, which resulted in more water stress later on in the growing season than for the early maturing variety. In a sensitivity analysis assuming no water stress larger differences in yields between both varieties were simulated (data not shown).

Intensification through high N rates was associated with an increase in transpiration in both crops, but the effect on other water balance components differed between maize and wheat. For example, wheat intensification decreased runoff, whereas maize intensification decreased drainage. With increased N rates, evaporation in wheat was also much more reduced than in maize. A possible explanation is that the wide row spacing of maize (0.75 m) leaves a larger part of the soil bare during a larger part of the growing season. This increases the risk of soil evaporation and runoff as total vegetation cover determines runoff to a large extent (Descheemaeker et al., 2006; Chen et al., 2010).

4.2 Prospects for yield gap closure and trade-off between intensification and water balance components

The CRV is characterised by large but differentiated yield gaps across HFZs (Getnet et al., 2015). This paper shows that there are good possibilities to close the prevailing yield gaps by combining a proper variety with appropriate N inputs for location-specific conditions.

To reduce the trade-off between water loss through evapotranspiration and increased production, location-specific input and management combinations should aim at maximum WUE. WUE increased with the N application rate, but varied by location, crop and variety. For the late maturing maize variety, the yield from the N rate at which WUE and gross margin were maximum (Table 6) exceeded the water limited yield (Yw) that was calculated from experimental data (Getnet et. al., 2015). For the early maturing maize variety, maximum WUE corresponded to about 80% of the Yw. For both wheat varieties, it was possible to close more than 80% of the yield gap using the N rate corresponding to maximum WUE and gross margins (Table 6).

At field scale, the trade-off between higher yields and increased crop water use (evapotranspiration) is particularly strong in maize. For wheat the trade-off was weaker because the increase in crop transpiration was associated with a decrease in soil evaporation, i.e. overall evapotranspiration hardly changed.

Intensification can lead to land saving as the same amount of grain can be produced with less land than for lower intensification levels. However, because of the trade-off with water losses through evapotranspiration, intensification should be accompanied by strategies to save land for other land uses, which potentially improve regulatory ecosystem services. These could include conversion of marginal land to natural vegetation (Descheemaeker et al., 2009) or carefully managed grazing land. Soil and water conservation practices on cultivated land would benefit regulatory water flows as well (Nyssen et al., 2010).

Table 6. The prospects of variety selection and N fertilization management options of maize and wheat in terms of closing prevailing yield gaps, and increasing water use efficiency and profitability across locations and selected soils in the CRV.

		Maize									Wheat								
		Eastern highlands (Luvisol)			Central lowlands (Andosol)			Western highlands (Vertisol)			Eastern highlands (Luvisol)			Central lowlands (Andosol)			Western highlands (Vertisol)		
Variety	N-rate (kg ha^{-1})	Yield (t ha^{-1})	WUE	Profit	Yield (t ha^{-1})	WUE	Profit	Yield (t ha^{-1})	WUE	Profit	Yield (t ha^{-1})	WUE	Profit	Yield (t ha^{-1})	WUE	Profit	Yield (t ha^{-1})	WUE	Profit
Early	20	○ 1.3	.4	$	◑ 3.4	.1	$	◔ 2.8	3	$	○ 1.2	.3	$	○ 1.7	.3	$	◔ 1.8	.9	$
	75	◔ 3.3	.2	$	◕ 5.3	.6	$	◑ 5.3	.5	$	◑ 3.3	.1	$	◑ 2.9	.2	$	◑ 3.2	.4	$
	125	◑ 6.1	.3	$	◑ 5.2	.3	-77	◑ 5.5	.5	$	◑ 4.5	.0	$	◕ 3.6	.8	$	◑ 4.1	.7	$
	175	◑ 6.3	.0	-30	◕ 5.2	.4	-67	◑ 5.5	.5	-66	◕ 5.3	.0	$	◕ 3.8	.8	$	◕ 4.6	0.0	$
	250	◑ 6.0	.5	[illegible]	◕ 5.3	.4	-99	◑ 5.5	.5	-100	◕ 6.0	.6	$	◕ 3.9	.1	$	◕ 4.8	0.8	$
	350	◑ 6.1	.5	-137	◕ 5.3	.4	-133	◑ 5.6	.5	-134	◕ 6.1	.7	[illegible]	◕ 3.9	.8	-132	◕ 4.8	0.1	-122
Late	20	◔ 1.9	.7	$	◑ 4.2	.0	$	◑ 4.4	.0	$	○ 1.2	.2	$	○ 1.8	.7	$	◔ 1.9	.0	$
	75	◑ 5.1	.2	$	◕ 5.7	.9	$	◑ 7.0	0.3	$	◑ 3.2	.1	$	◑ 3.0	.8	$	◑ 3.5	.6	$
	125	◑ 7.6	2.6	$	◕ 6.5	.8	$	◕ 9.1	2.7	$	◑ 4.9	1.4	$	◕ 3.5	.4	$	◑ 4.5	.4	$
	175	◕ 9.9	5.5	$	● 6.8	0.3	$	● 11.0	.7	$	◕ 5.9	.1	$	◕ 3.8	.5	$	◕ 5.0	1.0	$
	250	● 11.4	.3	$	● 6.9	0.4	-86	● 12.1	.2	$	◕ 6.7	.8	$	◕ 3.8	.9	$	◕ 5.2	1.7	$
	350	● 11.9	.2	[illegible]	● 6.9	0.4	-142	● 12.4	.4	-81	● 6.9	.8	-93	◕ 3.8	.7		◕ 5.3	1.2	-109

The shading in the circles represent classes of yield levels based on result in Table 4 of Getnet *et.al.* , 2015, under review.

○ Yield less than the Ya i.e. calculated from farmers' average in the respective HFZ

◔ Yield greater than Ya and less than the Ya95, calculated from best performing farmers in the respective HFZ

◑ Yield greater than Ya95% and less than 80% of Yw, calculated from experimental yield for the respective HFZ

◕ Yield greater than 80% of Yw and less than Yw, calculated from experimental yield for the respective HFZ

● Yield greater than the Yw calculated for the respective HFZ

Bars to compare the simulated water use efficiency (kg grain ha^{-1} mm^{-1}) at various N levels

$ N levels at which the benefit from additional yield exceeds the additional cost of N compared to the N level below.

4.3 Climate change effects

Climate change reduced future crop productivity by 15–25% for wheat and 2–30% for maize. Higher temperature associated with climate change drives a faster accumulation of thermal time, resulting in shortening of the growing period (Trudgill et al., 2005). For maize and wheat the maturity period was reduced by 19-21% and 12-16% (range between HFZs and variety), respectively. This implies that crops may not be able to utilize the available moisture of the full growing season. Under climate change, higher temperature enhances evaporation and transpiration (Table 4), and increases water stress (Bates et al., 2008; Moratiel et al., 2010). The effect of climate change on yield is stronger at higher N levels because the larger vegetative biomass increases water stress during possible dry spells.

Besides the strong effect on evaporation, climate change also led to reduced drainage (Table 4). At high N levels the reduction in drainage was smaller in maize than in wheat, because drainage under maize was already very low at high N levels under the current climate. For wheat though, the large amount of drainage water available at high N levels was strongly reduced by climate change.

4.4 Economics of N fertilization

The N rates at which maximum gross margins were attained were similar as for achieving maximum WUE. Although in most cases it is possible to increase gross margin up to 250 kg N ha^{-1}, the associated investment costs are high for smallholder farmers. Therefore, the access to fertiliser and availability of financial resources and credit facilities are important boundary conditions for increased N use by smallholders (IFDC, 2012).

We did not include other cost of N application (e.g. labour) or the possible additional benefit from the increase in biomass in this economic analysis. We also did not account for the larger risk associated with high N input, which was particularly evident for maize in Vertisols of the EH and Andosols of CL (Fig. 4).

5. Conclusions and recommendations

There is scope to increase crop yields through increasing N input far beyond farmers' current practice, even though yield variability can be large depending on location and soil type. Especially for maize in the highlands, variety selection is important to fully exploit the yield benefit from increased N input. Although less important than the use of fertilisers, further intensification though increased planting density is possible. Residue retention could also lead to additional yield benefits if constraints related to animal feed and land use arrangements in the current farming systems would be alleviated. We showed potential to attain at least 80% of the Yw in most HFZs and soils with N rates that result in high water use efficiencies as well as favourable cost-benefit ratios. These N rates amount to 250 kg ha^{-1} for late maturing and 75-125 kg ha^{-1} for early maturing maize varieties; and up to 250 kg ha^{-1} for both varieties of wheat. Agronomic experimentation needs to be conducted to verify the simulated outcomes of these N application rates, well above the presently "recommended" rates of N fertiliser,

Projected temperature increases under climate change tended to decrease yields in the CRV. Furthermore, the variability in yield increased with climate change, making farmers' decisions to select proper variety, management and input levels more risky. The trade-off between yield and water loss through evapotranspiration will be aggravated under climate change due to the increase in evapotranspiration on the one hand and the decrease in yield on the other hand. Hence, climate change will result in the need to use more agricultural land and water to produce the same amounts of cereals.

This field scale analysis provides insight in the potential to narrow the yield gap using different combinations of input use and management options. Although the potential is there, trade-offs between achieving high crop yields and increased water loss at field scale are unavoidable. Regional studies are required to better understand the wider implications of these trade-offs for the water balance and production goals in the Central Rift Valley.

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Annex I

Soil hydrologic properties of three soil types used in the SoilWat module

Soil type	Depth (cm)	BD (g cm^{-3})	LL (mm mm^{-1})	DUL (mm mm^{-1})	SAT (mm mm^{-1})
Andosols	0-20	1.190	0.195	0.355	0.497
	20-50	1.200	0.203	0.360	0.497
	50-75	1.140	0.180	0.376	0.535
	75-100	1.140	0.180	0.376	0.535
	100-125	1.160	0.202	0.392	0.535
	125-150	1.160	0.202	0.392	0.535
Luvisols	0-15	1.180	0.199	0.388	0.505
	15-30	1.220	0.199	0.405	0.490
	30-60	1.220	0.256	0.405	0.490
	60-90	1.225	0.256	0.434	0.488
	90-120	1.225	0.260	0.434	0.488
	120-150	1.310	0.260	0.434	0.488
Vertisols	0-25	1.100	0.240	0.337	0.500
	25-50	1.170	0.273	0.359	0.480
	50-90	1.400	0.336	0.442	0.470
	90-132	1.480	0.302	0.436	0.440
	132-200	1.300	0.253	0.381	0.500

BD=bulk density; LL= the soil water lower limit (at 15 bar pressure); DUL=soil water at drain upper limit of the soil; SAT= water content when the soil is saturate

Chapter 5

Regional analysis of intensification and water use: A gridded simulation using APSIM

This Chapter will be submitted as: Mezegebu Getnet, Katrien Descheemaeker, Huib Hengsdijk, Mink Zijlstra and Martin van Ittersum; Regional analysis of intensification and water use: A gridded simulation using APSIM

Abstract

This study aims to scale up promising intensification options from field scale to basin scale, aggregate basin scale production and to identify trade-offs between production and with water use for different land use scenarios. An automated gridded simulation procedure was developed to scale up results of the APSIM field scale model for maize and wheat across cultivated land in the Central Rift Valley (CRV) of Ethiopia. This procedure allowed designing land use scenarios based on a spatially explicit optimization of water use efficiency (WUE) and gross margin for each grid cell. Consequences of land use scenarios for food production and water use at basin level were evaluated. Across both crops, water use efficiency was highest at 125 kg N ha^{-1} in 44%, at 250 kg N ha^{-1} in 28%, at 20 kg N ha^{-1} in 19%, and at 175 kg N ha^{-1} in 9% of the cultivated land in the CRV. Gross margin was highest at 125 kg N ha^{-1} in 27%, at 175 in 26%, at 75 kg N ha^{-1} in 18%, and at 250 kg N ha^{-1} in 17% of the cultivated land in the CRV. The spatial optimization of gross margins is an entry point for developing spatially explicit recommendation of N rates in the CRV. Crop intensification to the level at which WUE and gross margin are maximised can meet projected food demand, i.e. 2 times (taking in to account the population increase), and 2.9 times the current production taking into account the population increase plus possible dietary change by 2050s while saving 1.7 x 10^5 ha (23%) for other land uses and services. These scenarios ensure a reduction in evapotranspiration from cropland by 60% and 30%, respectively, compared to the current cultivation practices at a low intensification level.

Key words: Gridded simulation, food production, water use, efficiency, gross margins, scaling up, land use scenario.

1. Introduction

Agriculture faces great challenges to substantially increase food production while decreasing its environmental footprint. Increasing crop yields and resource use efficiencies are necessary strategies towards meeting these challenges (Mueller et al., 2012). Assessment of the yield gaps and exploration of crop management options using field scale process-based models suggest great potentials to increase crop productivity through intensification in sub Saharan Africa (Kassie et al., 2014; Tittonell et al., 2008; Robertson et al., 2005; MacCarthy et al., 2009; Mupangwa and Jewitt, 2011). Field scale models are helpful to better understand the interactions among crop characteristics, environmental factors and management and their effect on crop productivity and crop-water relationships, but they do not give a complete picture of larger scale outcomes that are influenced by spatial heterogeneity and possible spatial interactions.

The Central Rift Valley (CRV) in Ethiopia is a typical example of a region with diverse agro-ecologies over short distances associated with large differences in altitude, e.g. annual rainfall may range from ca. 600 to 1200 mm within a distance of about 50 km. Land use change, climate change and water abstraction for irrigated horticulture have already affected the basin water balance in the closed CRV basin and the level of the terminal lake Abyata (Getnet et al., 2014). Basin scale understanding of the aggregated effects of future intensification of agriculture on crop production and the water balance is required for informed decision making, targeting interventions and setting priorities for a research agenda. Basin scale analyses of crop production and water use can be achieved by aggregating results of field scale crop models (Wesseling and Feddes, 2006) or by using integrated basin scale models like Soil and Water Assessment Tool (SWAT) (Baker and Miller, 2013). The choice for one of the two approaches depends on the purpose of the study and data availability. Here, the main focus is on the effects of crop intensification on basin-level crop production and water use. In SWAT the underlying processes of crop production are relatively simplified compared to field scale crop growth simulation models (Griensven et al., 2012) with limited potential to take into account varietal and management differences. Furthermore, such models require high quality and long term data of daily river flow for proper calibration and validation, which is a major limitation for the rivers in the CRV (Seyoum et al., 2015). Therefore, in this study, we used a grid-based crop simulation approach from which the results are aggregated to the basin level to gain insight in the effects of intensification on basin level food production and the trade-offs with the associated basin wide water consumption. We focused on the water depletion through evaporation and transpiration that are irrecoverably lost to the atmosphere and conducted the analysis for current climate conditions and selected intensification options, including variety choice and various nitrogen application rates.

Gridded simulation studies, using gridded soil information and alternative scenarios for food demand, are not yet very common for sub-Saharan Africa. However, the recently released large-scale, spatially explicit data on soils (Leenaars et al., 2015) now enables the assessment of trade-offs between food production, land use and water consumption at the regional level.

The objective of this paper is to scale up effects of crop management options that are promising in terms of narrowing yield gaps for two dominant cereal crops (maize and wheat) on basin production and water use. Based on a spatially explicit optimization of water use efficiency (WUE) and gross margin, we designed land use scenarios to evaluate the consequences on food production and water availability at basin level.

2. Materials and methods

2.1 Methodological framework

We used the field-scale Agricultural Production System sIMulator (APSIM) crop growth model to simulate basin level cereal production and water use in the CRV through a gridded simulation approach (Fig. 1). We used gridded data (1 x 1 km) of Root Zone Available Water Capacity (RZ-AWC), and effective rooting zone depth (ERZD) from the African Soil Information Service (AfSIS; Leenaars et al., 2015). A raster land use map of the CRV (MoWR, 2007) was prepared at the same resolution as the available soil map (1 x 1 km). Weather data from three representative weather stations i.e. Kulumsa, Melkassa and Butajira, were used for simulation at grids in the eastern highlands (EH), the central lowlands (CL) and western highlands (WH) respectively. We assumed that each grid cell is homogeneous in soil properties, weather and crop management. We did not take into account interaction among grid cells in terms of overland or groundwater flows. A GIS lookup table was used to link the proper combination of crop, variety, soil parameters, management rules and climate files to each grid cell. We modified the 'ApsimRegions' framework approach (www.apsimregions.org, last accessed on 13.02.2015) for the gridded simulation. ApsimRegions is a climate-crop modelling framework that links gridded weather data (rain, temperature, radiation, etc.) with the APSIM model. We developed a script using Python 2.7 to link and use the gridded soil and multi-location weather data sources in automated crop growth simulations for the large number (7172) of grid cells. For each grid cell, the program reads the RZ-AWC by soil layer and effective root zone depth. For the 0-30 cm top layer we used the aggregated RZ-AWC. For grid cells with soils deeper than 30 cm, we first subtracted the RZ-AWC of the 30 cm top layer from the total RZ-AWC, and then proportionally allocated the result to the layers below 30 cm to ERZD.

The program also reads the runoff curve number (CN) associated with each soil type, the crop type, variety type and associated crop management rules, and creates a unique APSIM setup to run the simulation (Fig. 1). Daily simulated outputs of the desired variables were exported into a SQLite database. An R script was developed to summarize the simulated grid cell data per year, whereas ArcGIS 10 was used for spatial analysis.

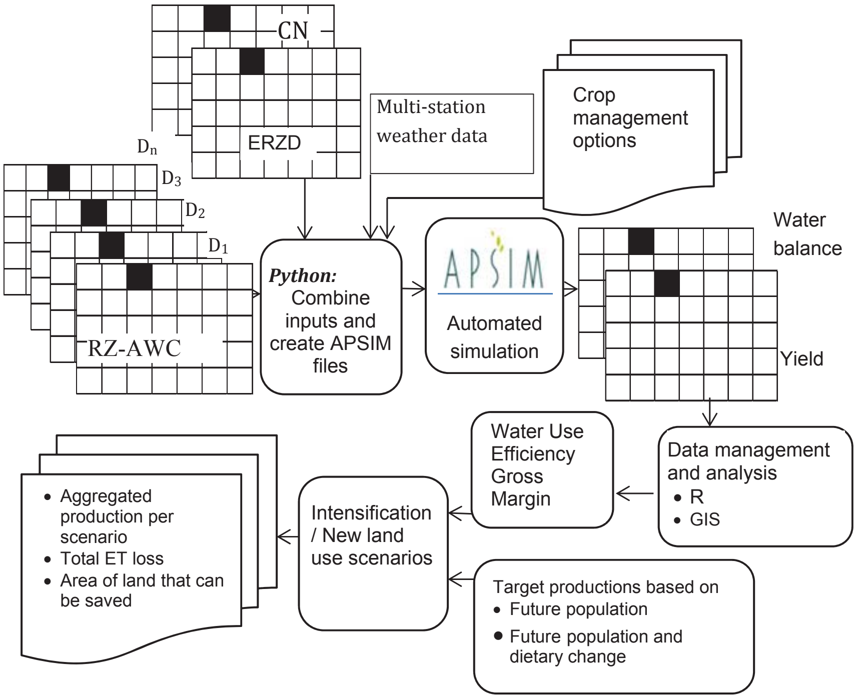


Figure1. Methodological framework for gridded simulation of yield and water balance components from cultivated lands in the CRV. D1, D2, ..., Dn are soil profile layers; *RZ-AWC*= Root Zone Available Water Capacity, ERZD=effective root zone depth, CN = runoff curve number, ET = evapotranspiration

APSIM simulated crop yields and the associated water balance were used to calculate water use efficiencies, whereas grain price and fertiliser costs were used to calculate gross margins per grid cell and management option of the cultivated land. Values per grid cell were aggregated to basin-level production and water consumption estimates.

2.1.1. APSIM model

The Agricultural Production System sIMulator (APSIM) is a field-scale crop growth model (Keating et al., 2003; Holzworth et al., 2014) that has been used in a wide range of applications, such as the assessment of impacts of crop management and climate change on yield and water balance. APSIM-SoilWAT simulates field scale water flows across profile layers using the hydrological properties of soils including the water content at lower limit (LL), drained upper limit (DUL) and saturation (SAT). We calibrated the model for runoff (Chapter 4) and used it to simulate the water balance for different soil types prevailing in the CRV (Getnet et al., 2015b). In this study, we used APSIM-SoilWAT to simulate the water balance of grid cells with cultivated land in the CRV. The APSIM maize and wheat models that have been calibrated for early and late maturing cultivars of both crops in the CRV (Getnet et al., 2015b) were used to simulate yield per grid cell.

2.1.2. Crop intensification options

Using APSIM (Chapter 4), we explored the effects on maize and wheat yields in the CRV of different crop management options, including different N rates, late and early maturing varieties and plant density. Based on this field scale analysis, the choice for the best performing options to be included in the gridded simulation are maize and wheat crops, late maturing varieties in the Eastern highlands (EH) and Western highlands (WH) and early maturing varieties in the Central Lowlands (CL). The best-performing planting density was 5.3 plants m^{-2} for maize and 250 plant m^{-2} for wheat across locations, varieties, farming zones and soils in the CRV (Chapter 4). Five N rates i.e. 20, 75, 125, 175 and 250 kg N ha^{-1} were used in the gridded simulation, because fertilization in combination with appropriate varietal selection was found to have high potential to increase yields in the CRV (Chapter 4). Other information on crop management included were planting rules within a specified planting window, which were set per grid cell depending on the crop (maize or wheat), variety (early or late maturing), and location (in EH, CL or WH).

2.1.3. Water use efficiency and gross margin

We calculated the water use efficiency (WUE) as the kg of grain yield per mm of water lost by evapotranspiration per year. Gross margins associated with N rates were calculated for each grid cell based on fertiliser costs and benefits from grain production as in Chapter 4. The N application rates that led to maximum WUE and maximum gross margin were identified for each grid cell. The production per grid obtained from these most efficient N rates were used to design new land use scenarios. In the land use scenarios, the consequences of choosing maximum gross margin or maximum WUE are explored.

2.1.4. Land use scenarios

We classified afro alpine, exposed surface, disturbed mixed high forest, plantation forest, open grassland, wooded grassland, shrub land, open shrub land, bush-shrub-grassland, marshland, open woodland, dense woodland, built-up areas and water bodies of the land use map (MoWR, 2007) as non-cultivated land. The moderately and intensively cultivated lands are categorized as cultivated land. The CRV consists of 11 districts which we divided into three Homogeneous Farming Zones HFZs, i.e. Eastern highlands, Central lowlands and Western highlands (Chapter 3). Major crops currently grown on the cultivated land in the HFZs include maize, wheat, flax, teff, beans and enset. In our simulations we assumed that all cultivated land was cropped with maize or wheat because (1) these are the dominant crops that comprise 49% of the cropland in the CRV (Table 3); (2) both crops are cultivated across all districts and HFZs allowing to compare yields and water balances across the districts and HFZs; and (3) calibrated and validated parameter sets for these crops were available (Chapter 4).

The actual area of wheat and maize per district (based on IFPRI, 2006) was used in a decision rule for assigning crops to grid cells for simulation. The proportions of both crops were calculated for all districts as:

$$Pm_i = \frac{Am_i}{Am_i + Aw_i}\,;\; Pw_i = \frac{Aw_i}{Am_i + Aw_i}$$

Where Pm_i is the share of maize area in the ith district; Pw_i is the share of wheat area in the ith district; Am_i is the area under maize in the ith district; Aw_i is the area under wheat in the ith district.

Subsequently, Pm_i (Table 3) was used to construct a binomial probability distribution for maize for each district. For each grid cell with cultivated land of a district, a value was randomly drawn from the distribution such that a Pm share of the grid cells in the district was assigned a value of one, and a Pw share was assigned a value of zero. If the value was one, maize was allocated to the cell; otherwise wheat was allocated.

Irrigation in the CRV is mainly used for vegetable production during the dry season following the harvest of rainfed crops that are cultivated during the main rainy season. The area of currently irrigated land was based on data in Getnet et al. (2014). The potentially irrigable area was defined by delineating a buffer zone around the fresh water resources and irrigation hotspots (MoWR, 2007) to take into account the possible expansion of irrigated land in the future. In this part of the CRV, therefore, the total evapotranspiration loss per year was computed as the evapotranspiration (ET) from the rainfed (maize and wheat) system plus the ET from the irrigated system, assuming 1.5 irrigated crops per year (Chapter 2). Irrigation water application rate and irrigation water use efficiencies for the CRV from (Van Halsema et al., 2011) were used to estimate the amount of water used by irrigated horticulture. The consequences of increasing irrigated land area and improving irrigation water use efficiency were analysed as part of the alternative future land use scenarios (Scenarios 3, 4 and 5 in Table 1).

The baseline (scenario 1) consisted of maize and wheat simulations at 20 kg N ha^{-1} for the current cultivated land. Current non-cultivated and current irrigated land with 35% water use efficiency (water requirement per water supplied), and 25% conveyance loss (Van Halsema et al., 2011) were also considered (Table 1). We assumed here that the current production levels of maize and wheat (6.67×10^5 and 6.64×10^5 ton yr^{-1}) reported by IFPRI (2006) meet the demand of the current population. Four future land use scenarios were formulated based on different intensification pathways and plausible increases in the food demand (Table 1). In scenario 2 the current agricultural land is cultivated with N rates resulting from two objectives, i.e. (a) maximum WUE and (b) maximum gross margin of maize and wheat (Chapter 4), while conveyance loss in the irrigated area is 5%. Scenario 3 uses the same intensification levels as scenario 2 but allocates only the most productive grid cells to maize and wheat until the current basin level grain production (IFPRI, 2006) is reached. Logically, in scenario 3 less land is cultivated and the idle land is treated as non-cultivated land. Furthermore, the irrigated horticulture area increases up to the potentially irrigable area in scenario 3. Recent forecasts suggest that the Ethiopian population will roughly double by 2050 (FAO, 2013). Focusing just on cereals, the demand is projected to increase with a factor 2.9 based on population increase and dietary and import/export changes (Rosegrant, 2012). We therefore considered a target production of 2.0 and 2.9 times the current production in scenarios 4 and 5, respectively. Intensification levels of maize and wheat and land allocation to both crops to achieve the production targets were similar to scenario 3. Irrigated land and irrigation water use efficiency in scenario 4 and 5 were as in scenario 3. Irrigation in the CRV is mainly for horticultural production in the dry season, and we considered its effect on basin level water use, not on cereal production, within the new scenarios. In the rainy season, the irrigated lands are used for rainfed cereal production, if those grid cells are allocated to maize or wheat to reach the target production levels. In that case, the associated water use and the contribution to cereal production are also considered.

Table 1. The five land use scenarios for the Central Rift Valley of Ethiopia, detailing the use and development of cultivated, non-cultivated and irrigated land.

	Scenario description				
	Cultivated land		Irrigated land for horticulture in the dry season		Non-cultivated land
Scenario 1 (baseline)	Total cultivated land allocated to maize and wheat based on the current proportion of both crops in each district within the CRV; Fertiliser rate is 20 kg N ha^{-1} for both crops, which represents current farmers' practice.	+	The current irrigated area (Getnet et al. 2014), current irrigation water use efficiency (35%), and 25% conveyance loss (Van Halsema et al. 2011)	+	Non-cultivated land (MoWR, 2007)
Scenario 2	Same as scenario 1 except that the N application is based on the rate at which maximum WUE, and maximum gross margin is attained per grid	+	Same as scenario 1, but conveyance loss is reduced to 5%	+	Same as scenario 1
Scenario 3	Same as scenario 2 except that only the most productive grid cells are allocated to maize and wheat for ensuring current grain production (IFPRI, 2006); idle land is allocated to non-cultivated land.	+	The irrigated area equals the potentially irrigable land, other assumptions same as scenario 2	+	Same as scenario 1 plus the idle land that is not cultivated anymore
Scenario 4	Same as scenario 3 except that the target production is 2 times the current production	+	Same as scenario 3	+	Same as scenario 1 plus the idle land that is not cultivated anymore
Scenario 5	Same as scenario 3 except that the target production is 2.9 times the current production	+	Same as scenario 3	+	Same as scenario 1 plus the idle land that is not cultivated anymore

2.2. Data

2.2.1. Soil data

Gridded maps of the Root Zone Plant-Available Water Capacity (RZ-AWC) (mm) and effective rooting zone depth (cm) were obtained at 1 x 1 km resolution for up to six profile layers from the AfSIS database (Leenaars et al., 2015).

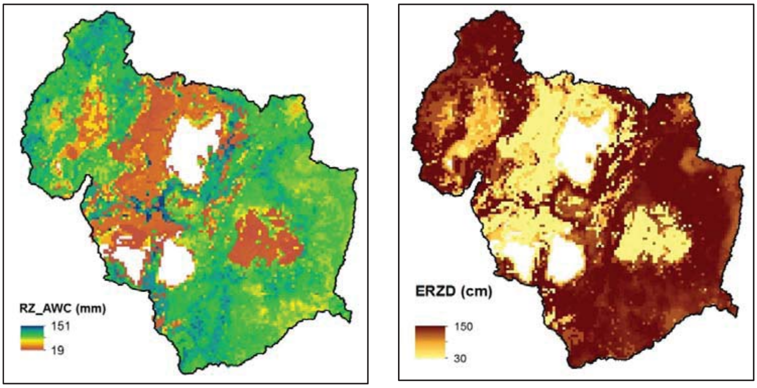


Figure 2. Spatial distribution of (a) Root Zone Available Water Capacity (RZ-AWC) in mm of the effective rooting zone, and (b) effective rooting zone depth (ERZD) in cm across the CRV.

Other soil properties of the major soils in the CRV (Table 2) including organic carbon, pH and initial nitrogen have been parameterized using the data in the soil map of the CRV (MoWR, 2007). Three of these soils, i.e. Luvisols (47% of the cultivated land in CRV), Andosols (12%) and Vertisols (10%) have been used to calibrate the parameters influencing the water balance components. These three major soils (70%) were assigned with the CN values previously calibrated to estimate runoff on these soils (Chapter 4). The CN values for the remaining five soil types (30%) have been allocated based on their similarity to the three calibrated soils with respect to the hydrologic soil group (HSG) and clay percentage as presented in Fig. 3 in Chapter 3. For example, Nitosols have the same hydrological soil group as the calibrated Luvisols, and hence inherited the CN value of Luvisols. We followed the same approach for the other soils. If the HSG does not completely correspond, we used the clay percent to interpolate the CN. The soil map with CN information was rasterized in the same resolution as the maps of RZ-AWC and ERZD, and used in the gridded simulation.

Table 2. Major soil types, their description and area extent within the Central Rift Valley.

	Soil type	Description	CN	Clay %	Silt %	Area (10^3ha)	% of the total area [1]
AN	Andosols	Deep to very deep; medium and coarse textured; well to excessively drained soils, HSG-B	78	22	39	104	10.1 (11.8)
CM	Cambisols	Shallow to very deep; sandy loam, sandy clay, loam and silty loam texture; and well to excessively drained soils HSG-D	86	48	29	102	9.9
FL	Fluvisols	Moderately deep to very deep; fine to medium textured and imperfectly to well-drained soils, HSG-C	84	26	39	14	1.4
LP	Leptosols	Very shallow; sandy clay, sandy clay loam; well to excessively drained soils, HSG-A	76	8	16	12	1.2
LV	Luvisols	Predominant soils with moderately deep to very deep; dominated by clay, clay loam, sandy clay loam and silty loam texture; moderately well to well drained soils, HSG-C	82	24	28	435	42.4 (47.4)
NT	Nitisols	Moderately deep to very deep soils with well drained & good permeability, favourable structure; and clay and clay loam texture, HSG-C	82	24	31	128	12.4
SN	Solonetz	Well drained, very deep, medium and coarse textured soils characterised by very alkaline PH and high exchangeable sodium percent, HSG-B	81	26	29	63	6.1
VR	Vertisols	Deep to very deep, fine and medium textured imperfectly to poorly drained soils, HSG-D	88	56	25	85	8.2 (9.8)

[1] The total percentage sums up to only ca. 92% because the remaining 8% accounts for water bodies and exposed rock surfaces. In parentheses is the percentage of the calibrated soils relative to cultivated land area. CN= runoff Curve Number. HSG=Hydrological Soil Group with HSG-A meaning low runoff potential, HSG-D is high runoff potential, and others in between. Numbers in brackets are percentages of the major soils relative to the cultivated land.

2.2.2 Climate data

Since the three HFZs of the CRV show substantial differences in climate, we used climate data of Kulumsa, Melkassa and Butajira to represent EH, CL and WH, respectively. These three stations had relatively complete records of daily data (21 years, 1989-2009) available which is required for reliable crop yield simulations (Grassini et al., 2015). Daily rainfall, minimum temperature, maximum temperature and solar radiation data of these stations were obtained from the National Meteorological Service Agency (NMA) of Ethiopia and used in APSIM to simulate yield and water balance components for each grid cell in the respective zones.

2.2.3. Land use data

The recent land use map of the CRV (MoWR, 2007) was used to define the cultivated land and non-cultivated land in the current land use. All the cultivated land was used in the gridded simulation to explore intensification options and was further used for defining new land use scenarios (Table 1).

2.3. Analyses

2.3.1. Maximizing WUE and gross margin

The WUE and gross margin were calculated for all N-rates at each grid. The N rates that led to maximum WUE and to maximum gross margin were identified and both were mapped for each grid in the CRV. Grid cells were ranked based on their performance in terms of WUE and gross margin. In the land use scenarios that target various production levels (scenarios 3, 4 and 5; Table 1), production from the top ranking grid cells that are sufficient to meet the targeted production was aggregated. Once the targeted production was reached, the less productive grid cells were assumed to be 'saved land' and converted into non-cultivated land.

2.3.2. Basin scale land and water for targeted production

Annual runoff, drainage, soil evaporation and crop transpiration (evapotranspiration – ET) for cultivated land were simulated using APSIM for every grid cell (section 2.1 and Fig. 1). The analysis of water use from non-cultivated land at basin level was done for two distinct cases, depending on the new land use scenarios. For scenarios 1 and 2 we used the non-cultivated land based on the 2007 land use map (Chapter 2). For scenarios 3, 4 and 5, the saved land was added to the non-cultivated land in scenario 1 or 2. We used the average ET per ha of non-cultivated lands in scenario 1 or 2 as the ET for saved land in scenarios 3, 4 and 5. For the non-cultivated land, we combined the reference evapotranspiration (ET_0) with the crop coefficients (Kc) corresponding to various vegetation types (Getnet et al., 2014) based on Allen et al. (1998) to estimate annual actual evapotranspiration (ETa). We used a stress factor (Ks) for vegetation types with shallow rooting depth to account for limited water availability in the dry season. For deep rooted vegetation such as forests and woodlands, we assumed that the deeper water layers can supply additional water, hence we did not consider Ks. Since ET_0 is an estimate of the evaporative demand of the atmosphere, we use it as a proxy to estimate water loss from water bodies. We assumed that actual evapotranspiration (ETa) from cultivated and non-cultivated land is irrecoverable water loss that can be used to compare the water use of various intensification levels at basin scale. Evapotranspiration per grid and total ET per basin were calculated for each future land use scenario. The area required to realize the targeted production and the corresponding water consumed through ET were also determined.

We used the rate of current agricultural land conversion and associated greenhouse gas (GHG) emission calculations by the Ethiopian Panel on Climate Change (EPCC, 2015) to discuss the possible benefits of saving agricultural land as a result of intensification on mitigation of GHG emission.

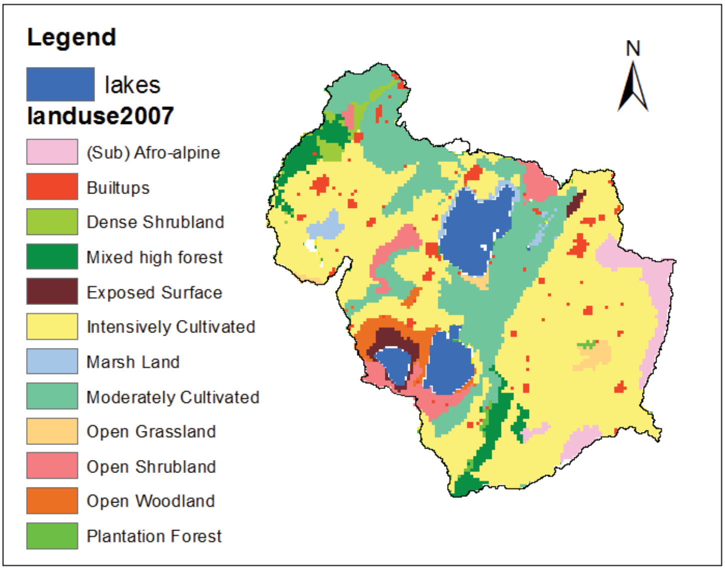
3. Results

Based on the current land use, about 70% of the area in the Central Rift Valley of Ethiopia is categorized as moderately and intensively cultivated land (Fig. 3a). Maize is dominantly cultivated in the western and central part of the basin, whereas wheat is dominant in the eastern part. Out of the 7.17 x 10^5 ha of cultivated land in CRV, about 44% was allocated to maize and the remaining 56% to wheat (Fig. 3b) following the relative proportions of these crops in the current farming system (Table 3).

Table 3. Areas covered by, and the relative proportion of maize and wheat under the current farming system, the area allocated for maize and wheat simulation in each district of the CRV.

	Actual crop area* (10^3 ha)		Proportion (0-1 scale)		Area allocated for simulation (10^3 ha)		
District (HFZ)	Maize	Wheat	Maize (Pm_i)	Wheat (Pw_i)	Maize	Wheat	Total
Dugda Bora (CL)	19.5	5.0	0.80	0.20	41.8	10.4	52.2
Adami Tulu(CL)	16.8	2.8	0.86	0.14	50.9	8.3	59.2
ArsiNegele (CL)	11.8	7.1	0.63	0.37	31.5	18.5	50.0
Zeway Dugda (CL)	12.9	7.0	0.65	0.35	48.6	26.2	74.8
DigelonaTeyo (EH)	0.5	13.0	0.04	0.96	3.2	77.7	80.9
Teyo (EH)	1.4	9.8	0.12	0.88	7.1	51.9	59.0
Munissa (EH)	3.7	17.6	0.18	0.82	17.2	78.6	95.8
Bekoji (EH)	0.8	18.4	0.04	0.96	3.6	87.1	90.7
Sodo (WH)	3.8	2.5	0.61	0.39	34.1	21.8	55.9
Meskanenamareko (WH)	9.7	2.2	0.81	0.19	43.3	10.2	53.5
Silte (WH)	4.0	1.8	0.70	0.30	31.6	13.6	45.2
Total	85.1	87.1			313.1	404.1	717.2
Weighted (by area) average			0.44	0.56			

* Data is based on IFPRI (2006). In brackets in the first column is the homogenous farming zone (HFZ) to which the district belongs: CL=Central lowlands, EH=Eastern highlands and WH=Western highlands



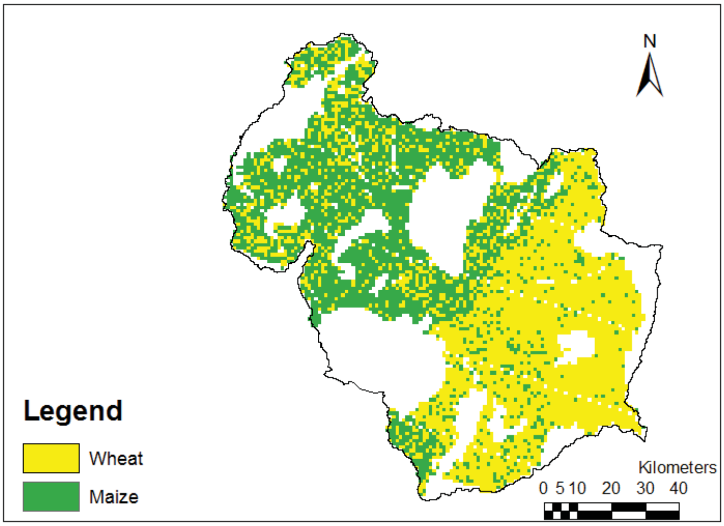


Figure 3. Current land use map (MoWR 2007) (a) and distribution of maize and wheat based on the proportional allocation to grid cells (Section 2.1.4) covering the cultivated land in the Central Rift Valley of Ethiopia (b).

3.1 Distribution of relative yield

Relative yield, i.e. the percentage of the yield in each grid cell relative to the maximum yield across all grid cells and N-rates, increased with increasing fertiliser rates (Fig. 4).

The minimum relative yield (of all grid cells) was 4% for the lowest N level and 15% for all other N rates. Low relative yields indicate the poor suitability of some grids for maize and wheat production even at high N level, which was attributed to the combined effect of low RZ-AWC and ERZD (Fig. 1). The maximum relative yield rapidly increased from 71% at 20 kg N ha^{-1}, to 88% at 75 kg N ha^{-1}, to 96% at 125 kg N ha^{-1}. Any further increase was relatively small for higher rates, i.e. 99 and 100% for 175 and 250 kg N ha^{-1}. This implies that it is possible to produce close to the potential by increasing the fertiliser application rate to 125 kg N ha^{-1} in large parts of the CRV (greenish colours in Fig. 4).

Average relative yields corresponding to the 20, 75, 125, 175 and 250 kg N ha^{-1} fertiliser rates were 29, 39, 45, 50 and 54% for maize, and 49, 67, 75, 78 and 78% for wheat. Generally, average relative yield was higher in EH (52-87%, across the N rates) and WH (39-78%) than in CL (23-29%). The variability in relative yield increased with larger fertiliser application rates (Fig. 4f).

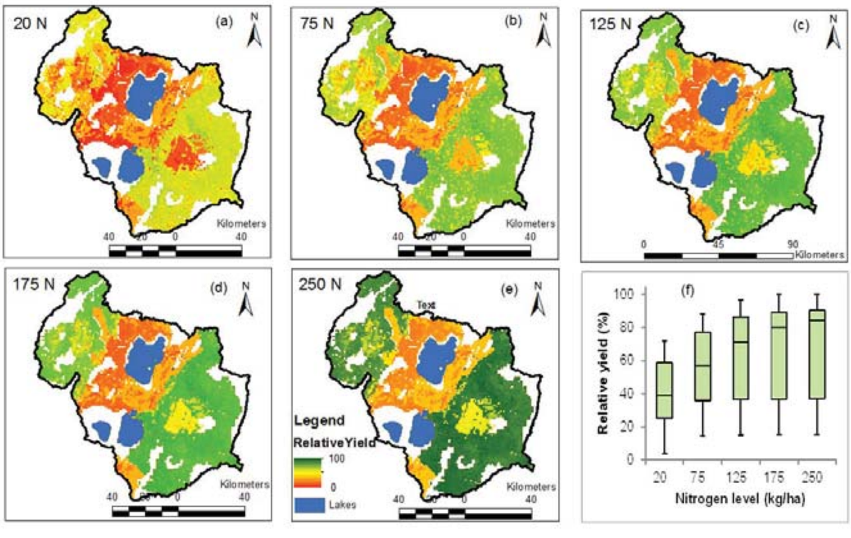


Figure 4. Relative yields of maize and wheat at various nitrogen rates (20, 75, 125, 175 and 250 kg N ha^{-1}) in the Central Rift Valley, Ethiopia. Relative yield was calculated as the percentage of the simulated maize and wheat yield in each grid cell relative to the maximum simulated maize and wheat yield across all grid cells and N-rates. Whisker plots show the distribution of relative yields within the CRV (7172 grid cells) for the five nitrogen rates.

3.2 Production and water use under various fertiliser application rates

Grain and stover production increased with increasing fertiliser rates for both maize and wheat (Fig. 5). A total of 1.24 M ton yr^{-1} and 1.32 M ton yr^{-1} of maize and wheat were produced in the basin under the baseline scenario (at 20 kg N ha^{-1}), which consumed 1610 and 1952 Mm^3 yr^{-1} of water through evapotranspiration, respectively. Basin-wide maize grain production increased up to 2.3 M ton yr^{-1} at 250 kg N ha^{-1} whereas that of wheat increased to 2.1 M ton at 175 kg N ha^{-1}, with no further wheat grain production benefit from more fertiliser application. However, wheat stover continues to increase up to 250 kg N ha^{-1}.

Generally, evapotranspiration increased with increasing fertiliser rates. The total amount of water lost through transpiration increased with increasing fertiliser rate for both crops (Fig. 5), but levelled off at higher N rates particularly for wheat. Water lost through soil evaporation decreased up to an N rate of 125 kg ha-1, above which, it levelled off (Fig. 5d). There was a corresponding decline in drainage as the N rates increased (Fig. 5f). Increasing N rates did not result in much change in runoff (Fig. 5e).

Basin maize production is less than wheat production at lower N-rates and greater at higher N rates because of the higher grain yield response of maize to N. Stover production however, is higher for wheat (Fig. 5b) at all N rates which can be explained by the larger wheat area and the lower harvest index of wheat (Chen et al. 2014).

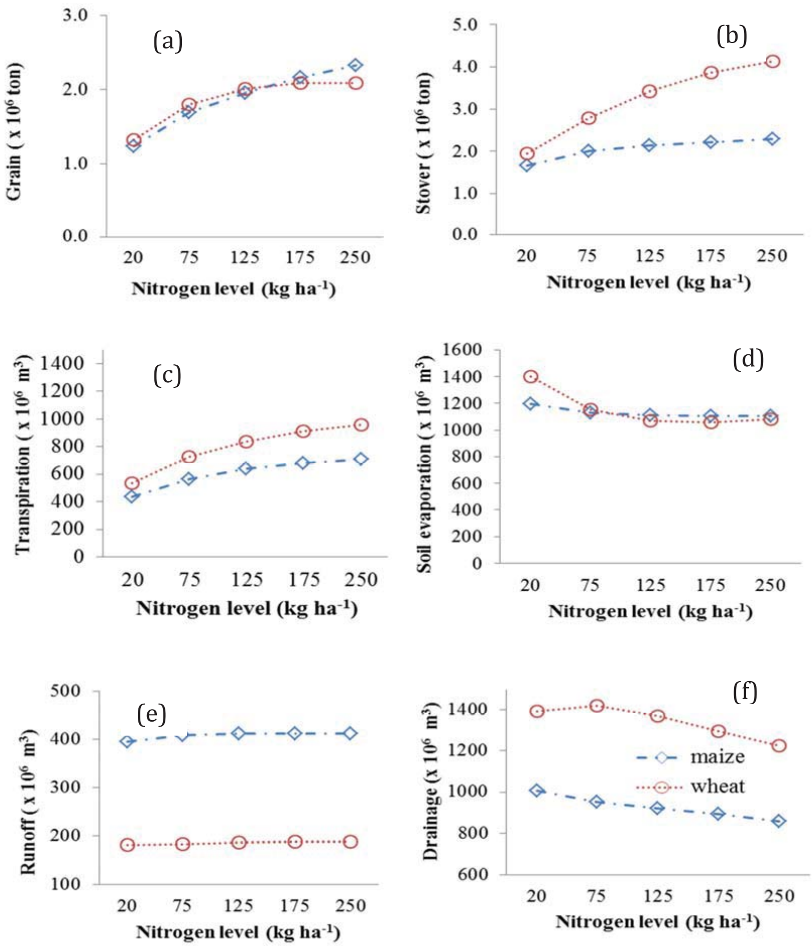


Figure 5. Total grain (a) and stover (b) production, and the corresponding total volume of water lost through transpiration (c), soil evaporation (d), runoff (e) and drainage (f) from cultivated maize and wheat land under various nitrogen rates in the CRV.

3.3 Production and water use at maximum WUE and GM

Maximum water use efficiency and gross margin were attained with the same N application rate in 63% of the grid cells (Fig. 6). In ca. 18% of the grid cells, maximum gross margin was attained at higher N rate than the N rate at which maximum WUE was attained. In ca. 19% of the grid cells the opposite was observed.

Water use efficiency was highest at 125 kg N ha^{-1} in 44%, at 250 kg N ha^{-1} in 28%, at 20 kg N ha^{-1} in 19%, and at 175 kg N ha^{-1} in 9% of the currently cultivated land (maize and wheat) in the CRV. Gross margin was highest at 125 kg N ha^{-1} in 27%, at 175 in 26%, at 75 kg N ha^{-1} in 18%, and at 250 kg N ha^{-1} in 17% of cultivated lands in CRV. Maximum gross margins and water use efficiencies were attained at lower N-rates in CL than in EH and WH (Fig. 6).

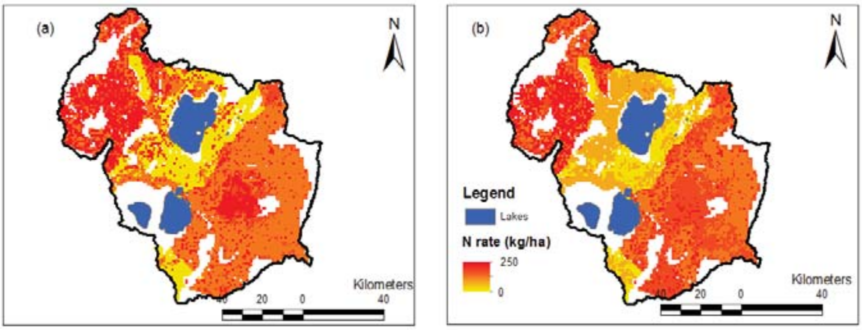


Figure 6. Simulated nitrogen rates at which (a) maximum water use efficiency (WUE), and (b) maximum gross margin of maize and wheat was attained (scenario 2).

In scenario 2, about 2.32 M ton maize and 2.03 M ton wheat was produced at maximised WUE, which resulted in 1722 Mm^3 and 1981 Mm^3 ET, respectively. About 2.29 M ton maize and 2.04 M ton wheat was produced at maximised gross margin, which resulted in 1709 Mm^3 and 1989 Mm^3 ET, respectively.

3.4 Targeted production in CRV

The simulated and aggregated production from scenario 1 (section 3.2), i.e. based on farmers' current average N rate of 20 kg ha^{-1}, is higher than the current production levels reported by IFPRI (2006). This is because, although farmers' average N-level is mimicked in the simulation in the base scenario, other sources of yield loss by farmers including pest, disease, weed, harvesting losses and the inability to perform timely farm operations by smallholder farmers are not accounted for in the simulation.

In scenario 2, i.e. production aggregated using the yield levels in the entire area at the N rates at which maximum WUE, and /or maximum gross margin is attained per grid, allowed to produce up to 87% more maize and 55% more wheat compared with the production from scenario 1.

The target maize production in scenario 3 (Table 1) was attained from the 17% most efficient production areas (5.3 x 10^4 ha), i.e. grid cells with maximum WUE and gross margin in the CRV. The most productive maize land was located in the western and eastern parts of the CRV and the irrigated horticultural areas in the Central Lowlands would not be cultivated with cereals in the rainy season (Fig. 7). The associated water use (ET) from the maize production totalled 301 Mm^3 (19%) at maximum WUE or 303 Mm^3 (19%) at maximum gross margin compared to the 1610 Mm^3 total ET under the baseline scenario (Table 4). Wheat required more land than maize to attain the target production, i.e. about 1.1 x 10^5 ha (27%) of the wheat area is required by maximizing WUE or gross margins. This caused a total ET of 524 Mm^3 if maximizing WUE or 527 Mm^3 if maximizing gross margins. Irrigated horticulture under scenario 3, 4 and 5 consumed 355 Mm^3 of water through evapotranspiration of 1.5 irrigated cropping seasons yr^{-1}.

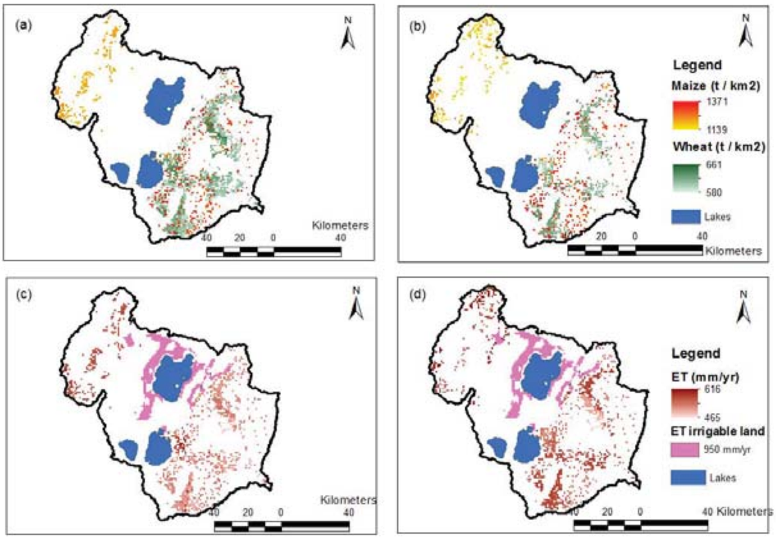


Figure 7. Results for Scenario 3: production per grid (1 km^2) from grid cells that are required to attain a target production equal to the current amount of maize and wheat produced in the CRV (IFPRI, 2006) based on (a) maximizing water use efficiency (WUE), (b) maximizing gross margin; and, respectively in (c) and (d), the associated evapotranspiration (ET) in mm yr^{-1}.

Doubling the target production (scenario 4) required a little more than doubling the area (a factor of ca. 2.06) of maize and wheat. The volume of water needed to produce maize and wheat also increased by a factor 2.13 and 2.04 (Table 4). This scenario brought more maize land into production in the western highlands, and more wheat land in the eastern highlands (Fig. 8). As in scenario 3, rainy season cultivation of cereals in the irrigated areas of the Central Lowlands would not be needed (Fig. 8).

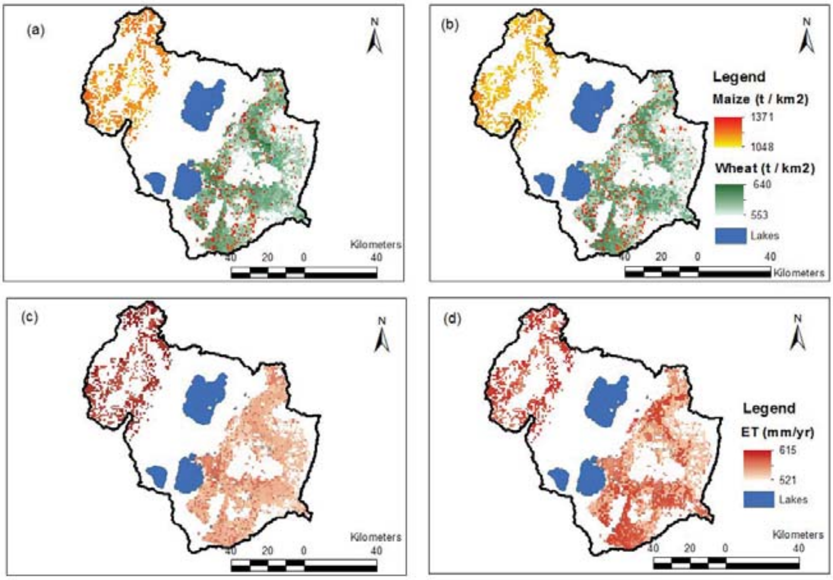


Figure 8. Results for Scenario 4, i.e. production per grid (1 km^2) from grid cells that are required to attain a target production of twice the current amount of maize and wheat produced in the CRV (IFPRI, 2006) based: (a) maximizing water use efficiency (WUE), (b) maximum gross margin; and, respectively in c and d, the associated evapotranspiration (ET) in mm yr^{-1}. Irrigated lands are not presented in the map due to possible overlap on some grid cells of rainfed cereal cultivation and irrigated horticulture

Scenario 5 required a larger cultivated area compared with scenarios 3 and 4 (Table 4). As the target production was 2.9 times the current production, much of the less productive areas of the CRV that were not cultivated in scenarios 3 and 4 were cultivated in scenario 5. About 65 and 87% of the current maize and wheat areas, respectively, were cultivated in scenario 5, including part of the irrigated horticulture areas.

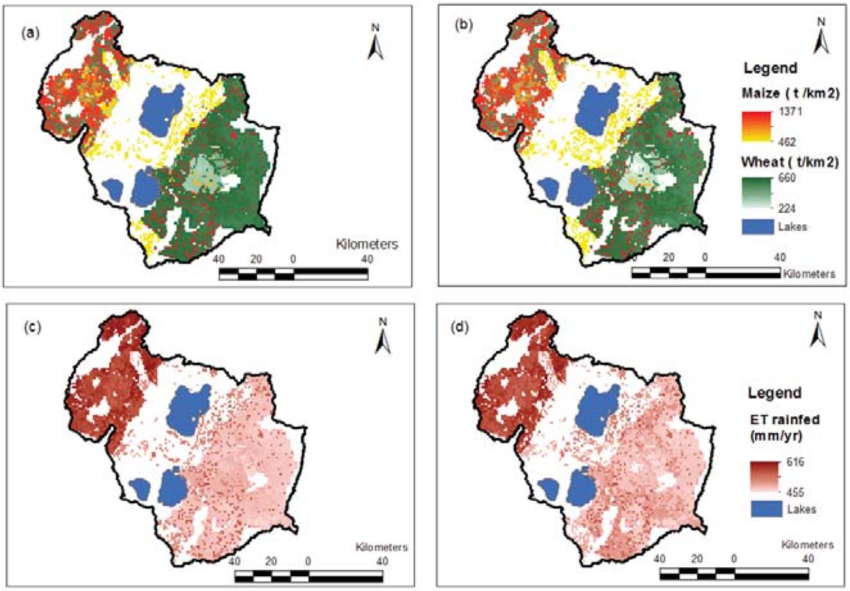


Figure 9. Results for Scenario 5: production per grid (1 km^2) from grid cells that are required to attain a target of 2.9 times the current maize and wheat production in the CRV (IFPRI, 2006) based on: (a) maximizing water use efficiency (WUE), (b) maximizing gross margin; and, respectively in c and d, the associated evapotranspiration (ET) in mm yr^{-1}. Irrigated lands are not presented in the map due to possible overlap on some grid cells of rainfed cereal cultivation and irrigated horticulture.

Table 4. Area required to produce the targeted maize and wheat production, and the associated evapotranspiration under various scenarios in the central rift valley of Ethiopia. WUE = water use efficiency; GM = gross margin; the area under the scenarios 1 (base) and 2 (in bold) represent the total area covered with maize and wheat in the simulation.

Crop	Scenario	Area at max WUE		Area at max GM		ET at max WUE		ET at max GM	
		(10^3 ha)	% from baseline	(10^3 ha)	% from baseline	Volume (Mm^3)	% from baseline	Volume (Mm^3)	% from baseline
Maize	Baseline (1)	**313**		313		1610		1610	
	2	**313**	100	313	100	1722	107	1709	106
	3	53	17	53	17	301	19	303	19
	4	109	35	110	35	640	40	643	40
	5	200	64	205	65	1140	70	1155	72
Wheat	Baseline (1)	**404**		404		1952		1952	
	2	**404**	100	404	100	1981	101	1989	102
	3	110	27	108	27	524	27	527	27
	4	226	56	223	55	1066	55	1069	55
	5	351	87	346	86	1693	87	1687	86
Total area of maize and wheat in the baseline		717		717					
		Area (10^3 ha)				ET (Mm^3)			
Irrigated horticulture	Baseline (1)	19				170			
	2	19				114			
	3,4,5	59				355			
Non-cultivated land *	Baseline (1)	219				1657			
	2	219				1657			
	3	775				5529			
	4	603				4228			
	5	385				2578			
Lakes and marsh land	Scenarios 1-5	92				1644			

*the non-cultivated land in scenarios 3, 4 and 5 includes the saved land due to intensification in cultivated land

4. Discussion and conclusions

4.1 Water use efficiency and gross margins

The rate of response to N of wheat stover was higher than that of grain, with stagnating grain production at higher N application rates (Figure 5), similar to another study showing a decreasing harvest index with increase in N input (Kidra.et.al., 2001). This is mainly observed in the late maturing wheat variety, suggesting that the response could be variety sensitive. However, information from experiments on biomass partitioning in response to N application rates for the varieties used in the simulation is scarce. We applied 50% of the N input at planting and 50% at 35 days after planting. Further splitting of the higher N-rates in particular may affect N availability across the growing season and that could change the response curve.

Maize intensification under the land use scenarios 3, 4 and 5 can be realized with WUE of 22, 21 and 17 kg ha^{-1} mm^{-1}, respectively (averages of 21 years and all grid cells in each scenario). This is fairly similar to the WUE calculated from maize experiments at optimal fertility, i.e. ca 20-25 kg ha^{-1} mm^{-1} (Amoah et al. 2012). Similarly, wheat intensification ensures WUE of 13, 13 and 11 kg ha^{-1} mm^{-1} under the land use scenarios 3, 4 and 5, respectively. In our scenario analysis, we maximised WUE and gross margin for two reasons, firstly to mitigate the trade-off between cereal production and water use and secondly to consider yield levels that are more realistic to obtain than the water-limited potential yield. Yet, the yield levels that are based on maximization of WUE and gross margins are higher than 80% of Yw, which is often found an upper limit of yield gap closure to be achieved in reality (Cassman, 1999; Cassman et al., 2003). Reasons for this yield plateau in practice relate to farm economics, environmental implications of targeting Yw and the difficulty of anticipating farm management to unknown weather. In the present assessment in which WUE is maximised, yield levels go up to 95-96% (range between crops) and 88% of Yw respectively In case we take 80% of Yw as upper limit, maize would require 4 and 12% (of total maize area) additional land and wheat would require 6 and 13% (of total wheat area) additional land to realize food production for scenarios 3 and 4, respectively. Scenario 5 requires the entire crop land area to be cultivated to satisfy only up to 95% of the target production, hence land saving will not be possible.

Considering only the cost of fertiliser and the benefits from grain yield, the average (of all grids per each crop) maximised gross margin from maize and wheat is estimated at 1363 and 1579 $ ha^{-1}, respectively. Gross margins are generally lower in the central lowlands compared with the gross margins in the eastern and western highlands. Associated with the higher price from wheat, the gross margin of wheat is higher than that of maize, even though the productivity is lower. Obviously, gross margins will change when other costs are accounted for (e.g. labour, seed and other inputs) and other benefits (e.g. stover) are considered.

Maximum WUE and maximum gross margin are obtained at the same N-level in only 63% of the cultivated land. Where maximum gross margin is attained at lower N-rate than the N-rate at which WUE is maximised (19% of the grids), the lower N-rates are more realistic because further increase of N-rates is not profitable anymore. Where maximum gross margin is attained at higher N-level than the N-level at which WUE is maximum (18% of the grids), there is a trade-off between economic and environmental considerations. Beyond our theoretical exercise of maximizing WUE and/or gross margins, practical considerations, such as access to fertiliser and credit, determine feasible N application rates and thus the degree of intensification that is achievable.

4.2 Saving land and water and mitigating GHG emission through intensification

Increasing productivity through intensification to the level at which WUE and gross margin are maximised potentially allows to save large areas for other land uses and services. Based on the gridded simulation, maize intensification in scenarios 3, 4 and 5 saved about 83, 65 and 35% of the land compared with the baseline (scenario 1). Similarly, wheat intensification saved about 73, 45 and 14% of land in the same scenarios, respectively.

The increased cereal production as a result of the crop intensification in the land use scenarios suggest that it is possible to produce 2.9 times more food to feed the increasing population in the CRV, taking into account also possible dietary change. At the same time the less productive land can be spared and used for other land uses and services. Saving land implies that it is possible to mitigate land use expansion and even to revert the large expansion of cultivated land taking place between 1990 and 2007 (Chapter 2).

Campbell et al. (2014) explained that sustainable intensification is an essential means of adapting to climate change, resulting in lower greenhouse gas (GHG) emissions per unit of output. Burney et al. (2010) also showed that while emissions associated with fertiliser production and application will increase under crop intensification, the net effect of higher yields is reduced GHG emissions. Therefore, slowing down current land use change has a particular importance in Ethiopia where ca 1.2 x 10^6 ha non-cultivated land is annually converted into cultivated land resulting in an additional emission of ca. 130 x 10^6 tons of CO_2e per year (EPCC 2015), i.e. ca. 107 tons of CO_2e emission per ha per year. In the CRV, an estimated area of 554 x10^3, 382 x10^3 and 166 x10^3 ha land could be saved at maximum WUE under scenario 3, 4 and 5, respectively. By implementing SI, further agricultural land expansion and the associated GHG emissions could be avoided. Furthermore, when cultivation is abandoned in the least productive areas, other land uses (e.g. grazing land, forest, natural vegetation) may appear that have a carbon sequestration potential. However, the allocation of the saved land to other land uses should be based on a further exploration of multiple objectives and optimization of alternative land uses.

The ability to produce target maize productions in scenarios 3, 4 and 5 from less land allows to reduce water loss through evapotranspiration from agricultural land by ca 80, 60 and 28%, respectively compared to the baseline. In the same scenarios, target wheat productions resulted in ca. 73, 45 and 14% lower ET losses from agricultural land. Hence, intensification has the potential to reduce water consumption per unit of agriculture production considerably in the CRV. The overall effect on the stressed basin water balance, particularly for lake Abyata, however, depends on the type of land use assigned to the saved land. In the irrigated system, unless the efficiency is improved, ca. 170 Mm^3 of water continues to be lost every year from the currently irrigated land. Given the favourable enabling environment, irrigation is expected to expand further to all the irrigable lands. This may increase the water lost by irrigation to ca. 355 Mm^3 yr^{-1}. Furthermore, 1657 Mm^3 yr^{-1} of water is lost through evapotranspiration from non-cultivated land uses under scenarios 1 and 2, whereas 1644 Mm^3 yr^{-1} is lost from water bodies.

Under scenarios 3, 4 and 5, in addition to the non-cultivated land under the base scenario, the non-cultivated land includes the land saved as a result of intensification. Assuming for the saved land a similar composition of non-cultivated land use types as in the base scenario, the total basin level water loss from non-agricultural land, water bodies, irrigated fields and cultivated lands is estimated at ca. 7000 Mm^3 yr^{-1} in the base scenario. The loss is ca 8300, 7900 and 7400 Mm^3 yr^{-1} from scenarios 3, 4 and 5, respectively. Hence, with this assumption on the allocation of saved land, there is no contribution of intensification to a reduction of the basin level water loss, despite the fact that intensification can reduce the ET per unit of cereal production.

The proportion of water that goes to the terminal lake Abyata depends on several complex factors including the type of land use the saved land is allocated for, and the surface and sub-surface flow routing and ground water dynamics.

Therefore, although reducing ET losses per unit of agricultural production has a positive impact on the water balance, detailed basin level hydrological modelling studies are needed to better understand the impact of flow routing.

4.3 Added value of gridded simulation approach versus field scale approach

Field scale estimation of yield and water balance at different N application rates was conducted using the same model (APSIM; Chapter 4) as used in this gridded simulation for the entire CRV. The simulated yield response to fertilisers in Chapter 4 differs from the simulated yield response in this chapter because of differences in soil characteristics. In Chapter 4, simulations were done for deep soils (>150 cm), whereas in this chapter a considerable number of grid cells had less deep soils. However, the available water holding capacity particularly in the top soil layers is larger for soils in the AfSIS data base compared to the soil profile information that was used in Chapter 4. This could have reduced simulated water stress particularly in the eastern and western highlands with higher rainfall resulting in a relatively higher yield from the gridded simulation using the AfSIS database.

Compared with a field scale approach (Muluneh et al*.* 2014; Kassie et al. 2015), the gridded simulation approach enabled to: (1) explore spatially explicit information on where to produce maize and wheat while optimizing gross margins and WUE; (2) assess the achievement of basin level production targets (based on projected food demand for future population) by aggregating field level yields; (3) generate spatial information on how much and where land and water can be saved under different production targets; and (4) identify spatially explicit fertiliser application rates that ensure high water use efficiency and high gross margin.

4.4 Effect of climate change on land availability

Climate change is expected to reduce future crop productivity by 15–25% for wheat and 2–30% for maize in the CRV by 2050s (Chapter 4). Kassie et al. (2015) also estimated (using field level simulation) an average yield loss of maize of 20% due to climate change. Such a drop in productivity will increase the area of land required to meet production under all the targeted scenarios. For example, assuming the worst case yield reduction due to climate change, i.e. 30% for maize and 25% for wheat, maize production at maximum WUE under scenario 3 and 4 would require 2.4×10^4 ha and 8.5×10^4 ha additional land respectively, compared with what is required without climate change. This is a 46% and 78%

increase, respectively. Similarly, with climate change under maximum WUE, wheat production would require 3.8 x 10^4 ha additional land to realize scenario 3 and 8.3 x 10^4 ha additional land to realize scenario 4, an increase by 34% and 37%. Furthermore, only 83% of the maize and 79% of the wheat target production under scenario 5 can be fulfilled from the existing land under climate change, and land sparing would not be possible.

The negative effect of climate change on basin water consumption is twofold. Firstly, the increase in temperature associated with climate change results in a shortening of the maturity period due to faster accumulation of growing degree days and hence a shorter growing period affecting evapotranspiration and crop water requirement. Secondly, the increased temperature due to climate change increases evapotranspiration per unit area (Moratiel et al. 2010; Chattaraj et al. 2014). Furthermore, the increase in CO_2 associated with climate change could increase wheat productivity.

5. Concluding remarks

Gridded simulation enabled to scale up promising intensification options from field scale to basin scale and explore effects of spatially explicit N rates on production, WUE, gross margins and required cultivated area. Furthermore, it enabled to aggregate gridded production for different land use scenarios based on the food demand of the growing population. Maximizing WUE and gross margin of SI options showed that it is possible to meet the food demand of future populations also taking into account the possible dietary change while at the same time saving large area of land and water for other ecosystem services. Climate change increases the amount of land and water required to produce the targeted productions, and reduces the size of land that can be saved by intensification. Future studies need to conduct experiments at representative sites to verify the simulation results, and to study the required social and policy interventions for a sustainable implementation of the tested intensification scenarios.

Generally, it is important that the allocation of the saved land to other land uses should be preceded by exploring the effects of multiple objectives, and analysis and optimization of alternative land uses.

Acknowledgement

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Chapter 6

General discussion

1. General discussion

1.1 Methodological and data considerations

The general objective of this study was to diagnose and quantify problems related to the water balance and low land productivity in the Central Rift Valley of Ethiopia (CRV), and to explore sustainable intensification (SI) options while understanding the trade-offs with water use under a variable and changing climate. Hence, the thesis focused on how to achieve simultaneously the two major development objectives in the CRV, i.e. sustainable use of land and water, and feeding the growing population (ca. 3 % per year) in the CRV.

To achieve the objectives of the thesis (Chapter 1), the four iterative phases of the DEED framework: Describe, Explain, Explore, and Design (Giller et al., 2008) have been followed (Figure 1.1).

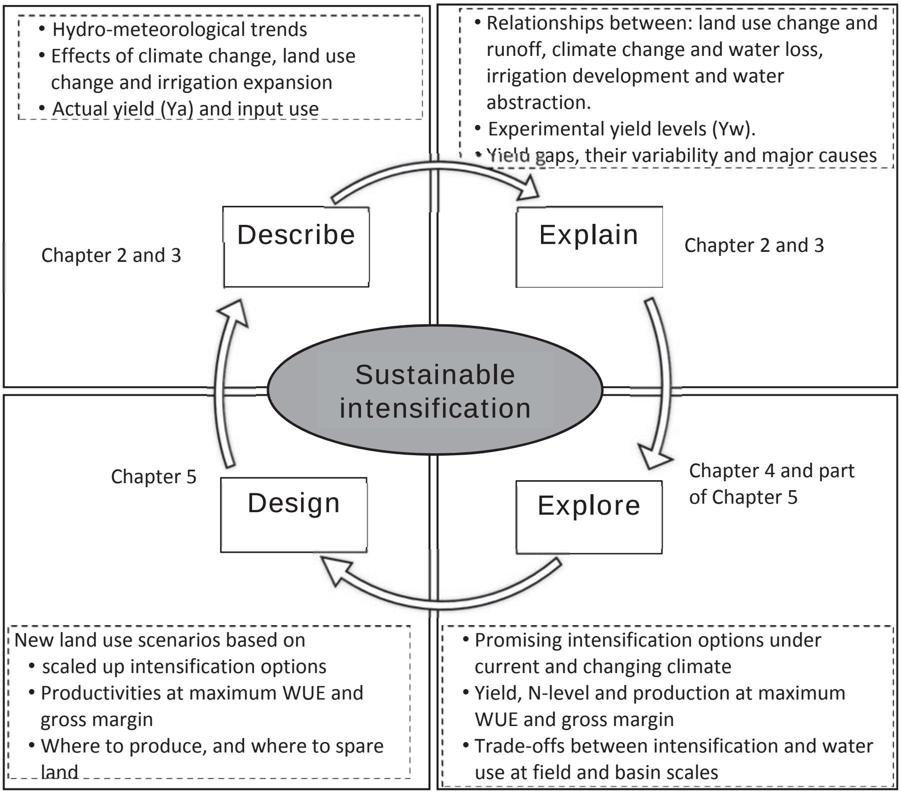

Figure 1.1 The DEED research cycle was followed to achieve the objectives of the thesis. Adapted from (Giller et al., 2008).

The DEED framework has been specifically developed as a research cycle to integrate knowledge across scales and disciplines, which can feed into participatory stakeholder processes. Here, I summarize what this thesis has contributed in each of these phases.

Describe: The descriptive aspects of the thesis involved quantifying climate, land use and water resources, and the historical trends and dynamics of evapotranspiration, river flows and lake levels within the closed basin of the CRV (Chapter 2). Subsequently, current production levels, resource use and yield gaps of maize and wheat across farming zones in the CRV have been quantified (Chapter 3).

Explain: The study combined different methods (Chapters 2 and 3) at field and basin level to explain relationships between land use change and runoff, climate change and water loss, irrigation development and water abstraction. Chapter 3 gave quantitative explanations of current productivity and yield gaps in maize and wheat and associated resource use efficiencies, as well as the underlying temporal and spatial variability of actual yields (Ya), water limited yields (Yw) and yield gaps (Yg).

Explore: Chapter 4 explored intensification options for maize and wheat using a crop growth model and simulating a large set of combinations of Genetic x Environment x Management factors that influence crop productivity and water use at field scale. Chapter 5 explored water use efficiencies (WUE) and gross margins associated with intensification options and generated spatially explicit information about N levels at which WUE and gross margins are maximised.

Design: A number of promising intensification options were subsequently used in Chapter 5 in the design of new land use scenarios for the CRV. For these scenarios, I analysed the implications for aggregated production and potential trade-offs with water use at basin level. The design phase allowed assessing the contribution of the intensification options to the food requirements for a growing population, taking into account possible dietary changes in the future. Furthermore, the use of maximum WUE and gross margins as the design criteria for the new land use scenarios enabled to assess the compromise between these criteria and the one that maximizes production (based on Yw).

The study covered a comprehensive spectrum from diagnosis of problems (related to current productivity, water and land use as well as climate change), through exploration of intensification options under current and future climate, to scaling up and design of new land use scenarios based on promising options. This broad analysis of the issues at stake may complement other recent studies that focused on the relationships among agricultural production, water and climate in the CRV (Muluneh, 2015; Kassie, 2014; Biazin, 2012).

This study focused on two hierarchical levels to analyse agricultural systems (Ewert et al., 2009), i.e. field and regional level (referred to as basin scale in this thesis as hydrologically delineated boundaries were used). At field scale yield gaps (Chapter 3) and intensification options (Chapter 4) for maize and wheat were quantified and analysed. At regional level the data management and spatial analytical tools of ArcGIS 10.2.1 were applied to analyse the dynamics in the basin-wide water balance (Chapter 2), and to scale-up promising intensification options (Chapter 5). The analysis at basin scale helped to assess the ability to produce sufficient amounts of food to feed future populations in the CRV.

A missing link between field and basin level in this thesis was the farm level at which land use decisions are made. At farm level management decisions need to be made and implemented that enable achieving the theoretical crop yield levels simulated in this thesis. Also at farm level decisions with respect to use of irrigation water are made which affect the overall basin water balance. Policy measures as part of the Design phase can enable, guide or enforce farmers' decision-making to achieve productivity increases or more efficient water use. Therefore, follow-up studies in the CRV should focus on the nexus between farm level decision-making and the policy environment.

This thesis combined different data types from different sources and time periods for the different research purposes (Table 1.1). Especially, the combination of Central Statistics Agency (CSA) farm survey data, Ethiopian Institute of Agricultural Research (EIAR) experimental yield data, and the recently released 1 x 1 km resolution soil information (Leenaars et al., 2015) was unique and provided new insights. The use of these databases in combination with spatial techniques provides new analytical capability to explain current crop productivity and resource use efficiency and to explore alternative cropping options.

However, the quality of the data sources remains a great concern under the prevailing conditions of Ethiopia. Weather and river gauging stations are sometimes poorly managed resulting in incomplete time series of data and the distribution of such stations is often not able to capture well the spatial variation of parameters in reality. For example, the density of the weather stations in the highlands of the CRV is rather thin while weather may change over short distances due to differences in altitude.

Table 1.1 Major data (purpose, period and source) used for different analyses in the thesis.

Data	Purpose	Period	Source
Climate	Trend analysis on rainfall, temperature and evapotranspiration	1975-2009	NMA, EIAR
Climate	Crop simulation, and WUE estimation	1989-2009*, 2050s (2039-2060)**	NMA & EIAR***
River discharge and lake levels	Trend analysis	1975-2009	MoWR
Land use	Analysis of land use change and associated runoff changes	2007 and 1990	MoA/ MoWR
Experimental yield	Estimation of water limited yield	2004-2009	EIAR
Experimental phenology	Calibration and validation of maize and wheat models in APSIM	2000, 2002-2005, 2007, 2008	EIAR
Field level survey	Estimation of actual yield and nutrient use	2004-2009	CSA
Soil Profile	Model setup and calibration		EIAR
Runoff	Model calibration for water balance estimation	2004 and 2007	EIAR
Gridded soil	Gridded simulation of production and water use		AfSIS

* the period for current climate scenario,
** the period for future/ changed climate scenario, and
*** data source for the current climate;
EIAR: Ethiopian Institute of Agricultural Research; NMA: National Meteorological Agency; MoWR: Ministry of Water Resources; MoA: Ministry of Agriculture; CSA: Central Statistics Agency; AfSIS: African Soil Information Service.

Information on ground water levels in the CRV was completely missing as it is not monitored systematically in Ethiopia. The flow data particularly from the Bulbula River was fragmented hindering the calibration and the use of detailed basin scale hydrological models. The use of hydrological models to predict effects of land use management on basin water flows is often difficult in data scarce situations such as the CRV (Seyoum et al., 2015). It is remarkable that recent data on water use, river flows and lake levels in the CRV are less available than the historical data. Current decision-making is severely hampered by such data scarcity, particularly because changes in land use, climate and irrigation water extraction have accelerated in the CRV in recent years.

The CSA farm survey data also had its quality problems and limitations because of changing district boundaries and variable names over the years. In recent survey data, the yield data from surveyed fields by CSA are directly measured from 4 x 4 m quadrants of sampled fields. This potentially is an improvement in the quality of collected data compared with the use of surveys in the past that registered yield information based on what farmers recall. However, crop management information in the survey data is still lacking which severely hampers understanding of the collected information.

The experimental data had its own limitations, although general experimental information on sowing dates, varieties, harvesting dates, etc. was readily available. The main problem for using the experimental data for the yield gap analysis was that in the experiments the applied nutrient rates were relatively low and uniform across locations. This may have resulted in lower fertilization levels than required for achieving the water-limited potential yields necessary for the yield gap analysis. Table 1.2 summarizes the strengths and limitations of the methods used across the thesis.

Table 1.2 Strengths and limitations related to the methods used in the thesis.

Method	Strength	Limitations
Statistical analysis of historical data	Enabled the quantitative description of the CRV water system using actual and historical hydro-meteorological and yield data	No causal relationships
Analysis of survey and experimental data	The use of historical CSA survey data and EIAR experimental yield data to describe current yield gaps and resource use.	Survey data lacks detailed agronomic management information
Crop growth simulation modelling	Enabled to explore promising intensification options and associated water use; formulate hypothesis to ensure sustainable intensification by combining a large number of Genetic x Environment x Management factors	Limited calibration data from well managed experiments; focused on maize and wheat crops only.
Productivity, WUE and gross margin as sustainability indicators	The selection of yield levels at which WUE and gross margin are maximised as benchmark gives insight in attainable yield, and more information than studies focusing on only water-limited potential yield as benchmark.	Indicators for social sustainability missing
Geo-spatial framework	Well-defined basin boundary to analyse land and water use and climate change impacts; aggregate field level survey data into homogeneous farming zones; scaling up field scale data to basin scale and design of land use scenarios with promising intensification options.	Lacks farm scale analysis
Gridded simulation	Combining the detailed process-based APSIM crop model with 1km resolution gridded soil information and multiple weather station data enabled to identify basin-wide productivity, N rates , WUE, gross margins; and the aggregated production and water use at basin level.	Does not consider flow routing and sub-surface and ground water dynamics within the basin

1.2 Prospects for sustainable intensification of crop production and trade-offs with the water balance

The prospects for sustainable intensification (SI) are discussed in view of the two major development objectives in the CRV, i.e. producing sufficient food for the increasing population, while at the same time ensuring sustainable use of limited water and land resources under variable and changing climate conditions.

Differences between the theoretical potential yield levels and actual farmers' yields define the yield gaps, and precise spatially explicit knowledge about these yield gaps is essential to guide SI of agriculture (van Ittersum et al., 2013). SI acknowledges that enhanced crop productivity needs to go hand in hand with the maintenance of other ecosystem services and enhance the resilience of systems to shocks (Vanlauwe et al., 2014). The goal of sustainable agriculture is to maximize the net benefits that society receives from food production and to make sure that ecosystem services are maintained for future generations. This requires increased crop yields, increased nutrient use efficiencies (NUEs) and WUEs, ecologically based management practices, and judicious use of pesticides (Tilman et al., 2002). However, the sustainability goals are diverse and they can seldom be realized to the full extent at the same time, and therefore trade-offs are unavoidable (Struik and Kuyper, 2014). Although there is limited consensus on the criteria for decision making and SI implementation (Struik et al., 2014; Tittonell, 2014), most definitions include the production of more food per unit of land and/or capital used, the preservation of important ecosystem services, and resilience to shocks and stresses, including climate change, as principles (Vanlauwe et al., 2014). In a more detailed way, Garnett et al. (2013) and Godfray and Garnett (2014) defined four underpinning premises of SI, situating it within a broader framework of priority actions for the food system: (i) the need to increase production; (ii) increased production must be met through higher yields because increasing the agricultural area carries major environmental costs; (iii) food security requires as much attention as increasing environmental sustainability; and (iv) SI denotes a goal but does not specify a priori how it should be attained or which agricultural techniques to deploy, and hence there is a need to consider a range of tools and production methods to achieve these goals.

The prospects for SI and the trade-offs with the water balance under the variable and changing climate are presented in this thesis. Based on the premises by Godfray and Garnett (2014), the following questions can be raised for the CRV: (i) What is the capacity to increase food production? (ii) Can intensification prevent further expansion of and even save agricultural land for other services and mitigate the pressure on natural resources, especially water resources? (iii) Does increasing environmental sustainability cause a reduction in production affecting food security? (iv) What are the key factors required to support the implementation of SI? In this thesis questions (ii) and (iii) are highly interrelated and these will thus be addressed simultaneously in the following sub-sections.

1.2.1. The capacity to increase food production

An increase in food production could be achieved by converting more non-cultivated land to agriculture or through increasing the productivity of the existing agricultural land. The agricultural area in the CRV increased from ca. 58% in 1990 to 70% of the total land in 2007 (Chapter 2). More than two third of the remaining non-cultivated land is comprised of lakes, built-up land, marshland, exposed surfaces and afro-alpine vegetation, which are not suitable for agriculture, while one third is mainly forest and shrub land predominantly in hilly areas. Therefore, there is little scope to increase production by further expansion of agricultural land in the CRV. Thus, the capacity to increase food production in the CRV depends on: (a) the window of opportunity to increase yields on existing agricultural land i.e. the yield gap; (b) the availability of intensification options to narrow yield gaps; and (c) the resilience of the production system given the variable climatological conditions in the CRV and their effects on the agricultural production (Chapter 3).

Yield gaps in the CRV are large, i.e. farmers produce only 17-36% and 30-43% (range across farming zones) of what is possible under optimum management for maize and wheat, respectively (Chapter 3). These yield gaps for maize are similar to the ones found in the Global Yield Gap Atlas (www.yieldgap.org), but for wheat the gaps found in the present study are smaller than the ones reported in the Atlas. The reason for this is that the estimates of Yw in Chapter 3 are lower than the ones reported in the Atlas, probably because the experimental data that were used in Chapter 3 do not fully reflect water-limited potential yields. The simulated Yw in Chapter 4 and associated Yg for both crops are much closer to the estimates in the Global Yield Gap Atlas (www.yieldgap.org). Particularly, the wheat Yw estimated in Chapter 4 is higher than that in Chapter 3.

The simulated yield response to fertilisers in Chapter 4 is lower than the simulated yield response in Chapter 5 because of differences in soil characteristics that have been used. Compared with the soil profile data used in Chapter 4, the available soil water particularly in the top soil layers is larger for the gridded soil data used in Chapter 5. This could have increased water availability particularly in the relatively wet eastern and western highlands.

Given the large yield gaps, there are opportunities to tackle the supply-side problem of food security at the field level. The land use scenarios at basin level (Chapter 5) showed that even food surpluses can be produced in the CRV. Such food surpluses could be utilized to supply food to production deficit zones in Ethiopia. Main management factors to close the yield gaps and to increase food production are the timely planting of crops, location-specific varietal selection and spatially explicit nitrogen (and other nutrients) inputs. There are, however, still a lot of practical challenges for farmers in the CRV to increase production (Sub section 1.2.4).

The resilience of the production system is important to consider in the context of the CRV because of the observed variability in rainfall (Chapter 2; Kassie et al., 2014). The average (of 7172 grids) temporal variation, expressed as coefficient of variation (CV), of simulated yield of maize and wheat across 21 years ranged between 29% (at low N level) and 30% at high N level for maize, and 15% (at low N level) and 27% (at high N level) for wheat (Chapter 5). These CVs are relatively modest, and suggest that under optimum management crop yields under both low and high N inputs are somewhat less affected by climate than some other studies suggest (e.g. Isik and Devadoss, 2006). By contrast, the average (over 21 years) spatial variation (CV), i.e. across all grid cells, was 46% at low N rate, and 56% at high N rate. Hence, spatial variation is high; however, leaving less productive grids out of crop production as a result of intensification at more productive grids will substantially reduce the spatial variability.

Climate change poses an additional risk to sustainability of the water and food production system in the CRV in particular and in Ethiopia in general. The thesis demonstrated that climate change, and in particular the increase in temperature over the past years, resulted in an additional large evaporative loss of water from land surface and water bodies (Chapter2). The anticipated change in climate by the year 2050 is estimated to reduce maize and wheat productivity by ca. 15-25% and 2-30%, respectively (Chapter 4). The anticipated lower yields under changed climate conditions are mainly associated with the possible water stress resulting from increased soil evaporation, and the shortening of the growing period due to increased temperature. This will have consequences for aggregated food production, i.e. more land and water will be required to produce the projected demand for food compared with a situation without climate change (Chapter 5). Future breeding and agronomic research in Ethiopia, therefore, need to consider the expected effects of climate change to make crop technologies climate smart.

1.2.2. Trade-offs between intensification and environmental sustainability

a. Land sparing

Narrowing yield gaps and increasing production through intensification allows producing more food from less land. This has particular importance in Ethiopia where ca. 1.2 x 10^6 ha of land is converted to agriculture each year (EPCC, 2015). An overall increase in production does not mean yields should increase everywhere or at any cost (Garnett et al., 2013). Some earlier studies in the CRV used the water-limited yield as a benchmark for increased yield (Kassie et al. (2014), Global Yield Gap Atlas, http://www.yieldgap.org/). This thesis used the N rates and yield levels at which WUE and gross margin are maximised as a benchmark. The production estimate from this approach is lower than the production using water-limited yield as benchmark because maximum WUE and gross margins are not necessarily achieved at water-limited potential yield. In general, maximum WUE and gross margins were attained in this study at 0-5 % and 0-12% below the water-limited potential yield, respectively (range between grids). Yet, the basin production estimate in this thesis is high enough to meet the targeted food needs of a future population in the CRV and beyond. Note, however, that these estimated yield levels are still higher than the often used criterion for exploitable yield gaps, i.e. 80% of water-limited potential yields (Van Ittersum et al., 2013). This implies it will be very challenging to realize such high yield levels even if it is profitable. Hence, the difficulty to move beyond 80% of the Yw could have a constraining effect on aggregated production. This would result in 4-6% additional land requirement to meet scenario 3 and 12-13% additional land to realize scenario 4 (range between crops) whereas land saving may not be possible under scenario 5.

In the CRV, an estimated area of 554 x 10^3 ha (77% of the current agricultural area), 382 x 10^3 ha (53%) and 166 x 10^3 ha (23%) of land could be taken out of production through intensification under scenario 3 (i.e. production for current population), scenario 4 (projected demand for the population in 2050), and scenario 5 (projected demand for population and dietary change in 2050), respectively. Because human activities are the major drivers for land and water use in the CRV (Temesgen et al., 2013; Garedew et al., 2009), reducing agricultural land use may have various benefits for the Abyata-Shalla Lake national park situated at the end of the CRV water system (Teferra and Beyene, 2014). Future research is needed on how the saved lands can be best used for other land uses, including the national park and tourism around Lake Langano to diversify the income and livelihood of the local population.

b. Mitigation of CO_2 emissions

SI is an essential means for agriculture to adapt to climate change, first to avoid agricultural area expansion leading to severe greenhouse gas (GHG) emissions and second because it may result in lower GHG emissions per unit of agricultural output (Campbell et al., 2014; Burney et al., 2010). In Ethiopia, ca.1.2 x 10^6 ha of land is converted to cultivated land every year as a result of which, Ethiopia emits ca. 130 x 10^6 tons of CO_2e per year (EPCC, 2015). By implementing SI, further agricultural land expansion and the associated GHG emissions could be avoided. Furthermore, when cultivation is abandoned in the least productive areas, other land uses (e.g. grazing land, forest, natural vegetation) may appear that have a carbon sequestration potential.

c. Water saving

Past and present developments in the CRV have resulted in a decreasing water level of Lake Abyata at an average rate of about 0.165 m yr^{-1} (Chapter 2). This estimate is similar to the estimate by Alemayehu et al. (2006) who showed a 5 m drop in the level of Abyata in three decades. The decrease of Lake Abyata is mainly related to a reduced inflow from its main feeding river Bulbula. This river receives its water from Lake Zeway and acts as an overflow of Lake Zeway water to Lake Abyata (Chapter 2; Ayenew (2007)). In the long run, a reduced overflow from Lake Zeway could affect the natural flushing of contaminants such as salts and nutrients from the freshwater Lake Zeway (fed by runoff from the upstream agricultural lands), potentially leading to serious quality deterioration threatening the environmental sustainability. The recent increase in water abstraction for irrigation purposes along the shores of Lake Zeway may further limit the overflow of excess water into the Bulbula River, thus posing an environmental risk, which needs better monitoring and more research.

Intensification of crop production increases water use at field level (Chapter 4). However, crop intensification allowed producing the target production with less water from agricultural land because less land is needed. It should be noted that, although the ET per unit of agricultural production could decrease as a result of intensification, the actual amount of ET at basin level or benefits from other ecosystem services from the saved land depend on the type of land use assigned to the saved land.

1.2.3. Key factors for implementing sustainable intensification in Ethiopia

Increasing current low crop yields in the CRV requires the selection of a location-specific mix of crop variety and management. This is particularly important in the

CRV where growing conditions change over short distances, associated with differences in altitude, resulting in spatially diverging yield potentials of maize and wheat. The thesis demonstrated that location-specific selection of varieties and N levels are more important decision variables for farmers to increase crop yields and narrow current yield gaps than crop residue management and planting density (Chapter 4). This result is in line with the study by Abate et al. (2015), which demonstrated that improved maize varieties and mineral fertilisers, coupled with improved extension services are key factors for the accelerated growth in maize productivity in Ethiopia. Because the nitrogen levels that maximize crop yields vary with locations (climate and soils), crop type and variety (Chapters 4 and 5), the 'blanket' fertiliser recommendation that is practiced in Ethiopia to date urgently needs revision.

To minimize the environmental impacts of intensification, increased nutrient application to narrow yield gaps should be complemented by efforts to decrease overuse of crop inputs wherever possible (Mueller et al., 2012). In most cases, the nitrogen level at which maximum yield was attained at field scale (Chapter 4) or regional level (Chapter 5) was higher than the N rate at which WUE and/or gross margins were highest. Hence, recommending the N-rates at maximum WUE and gross margins can help to avoided overuse of N compared with the N rate needed to maximize yield, which was 250 kg N ha^{-1} (the highest N rate tested) on 76% of the cropland (Table 1.3).

Table 1.3 Percentage of the total cultivated land for which yield, water use efficiency and gross margin are maximised for each N-rate.

	Nitrogen rate (kg ha^{-1})				
	20	75	125	175	250
Maximum yield (% of area)	0	4	7	13	76
Maximum WUE (% of area)	5	15	44	9	28
Maximum gross margin (% of area)	12	18	27	26	17

In contrast to the criteria-based planting in the crop simulations (i.e. 20 mm of rain in three consecutive days within an empirically based planting window), in practice timely planting is subject to uncertainties in weather and labour availability. Uncertainties in weather are fundamental constraints of agricultural production (Lobell et al., 2009). Farmers in Ethiopia generally lack meteorological seasonal forecast information, such as those based on El Niño phenomena, and short-term (< 3 days) and medium-term (between 3 and 10 days) weather forecast information, which may support agricultural decision-making to minimize climate-induced risks and utilize opportunities. Therefore, weather forecasting skills in Ethiopia need to be improved and weather services must be made available to enable farmers to take better-informed management decisions. As farm operations of most crops overlap, timely planting and other labour-intensive operations are subject to availability of family or hired labour.

Enabling policies, well-functioning input/output market and delivery systems, and the institutional capacity to implement food security and environmental sustainability measures are fundamental, if SI is to contribute to the food system in a country (Godfray and Garnett, 2014; Garnett et al., 2013). Such policies need to stimulate the availability and access to fertilisers and other inputs for farmers. Furthermore, the implementation of the land use scenarios at basin scale (Chapter 5) needs economic development and policies aimed at creating alternative livelihoods to the owners of the land that is no longer needed for agricultural purposes.

Water abstraction for irrigation consumes a large and increasing amount of fresh water resources in the CRV. Often, irrigation management is poor resulting in low irrigation water efficiencies and unnecessary water losses (Van Halsema et al., 2011). Water use saving policies need to be in place to promote more efficient irrigation management and minimize overall water use per unit of product.

In conclusion, implementation of SI principles in practice needs further research and exploration of the proper mix of socioeconomic, policy and institutional enabling conditions.

1.3 Conclusions

The key conclusions of this thesis are:

- Recent climate change increased evapotranspiration losses by 207 Mm^3yr^{-1} (1990-2007) from lakes and land surface; land use change resulted in an increase of net runoff of 260 Mm^3yr^{-1} (1990-2007), and water abstraction for irrigation increased from 20 Mm^3yr^{-1} in 2002 to 285 Mm^3yr^{-1} in 2009. All these three developments have affected the water system in the CRV;
- The scope for increasing food production in the CRV by expanding the agricultural area is limited because fertile land has become very scarce. To increase production the focus should be on crop intensification.
- Current input use in CRV is low (less than 20 kg N ha^{-1}) resulting in large yield gaps ranging between 4.2-9.2 t ha^{-1} for maize, and 2.5-4.7 t ha^{-1} for wheat (ranges across farming zones). Therefore, good opportunities exist for crop intensification and to increase crop production on existing cropland, although the possibilities vary across the CRV.
- Model-based exploration of intensification options can be used to prioritize promising options, and for quantifying trade-offs, for example, between

food production and water use. The gridded simulation approach can be applied by combining crop management options and climate scenarios to scale up benefits and trade-offs to the basin scale.

- The aggregated production from maximizing WUE and gross margin per grid is sufficient to meet the more than threefold increase in production demand in the CRV, while at the same time saving ca. 23% of the less productive current agricultural land for other land uses and services.
- The combined use of the CSA field survey data, EIAR experimental yield data and spatial soil data bases in this thesis has provided new insights and shows that such databases can be beneficially used beyond the purpose for which they were originally designed.
- Quantitative and spatial analysis of water flow routing is lacking in this thesis. Furthermore, more systematic and reliable data collection methods are required across different sectors (agriculture, water and economy) to address the complex resource use issues in the CRV.
- The key findings in this thesis can be a basis for further experimentation to verify and explain the identified yield gaps and the promising intensification options at representative soils and climate before implementing them.
- There is a trade-off between increasing agricultural production and water use at field level. However, at basin level, intensification allowed to produce the target production from less evapotranspired water from cultivated land. This means that intensification can influence the impact of cereal production on basin level water use and could lead to an increased amount of water reaching the downstream lake Abyata, depending on the land use assigned to the saved land.

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Summary

The Central Rift Valley (CRV) of Ethiopia (approximately 1 million ha) is a closed river basin where poverty and natural resource degradation are firmly intertwined. The livelihood strategy for the majority of the population in the CRV (ca. 2 million) is predominantly based on small mixed rainfed farming systems. The human population in the CRV will double within ca. 25 years if the current growth rate of ca. 3% is maintained. Feeding the growing population is a major policy priority in Ethiopia but food security is hampered by recurrent drought, traditional farming practices, and various socio-economic factors, such as poverty and poor infrastructure.

Since the CRV is a closed river basin, interventions in land and water resources, such as expansion of cultivated land and irrigation, have far-reaching consequences for ecosystem goods and services, and potentially undermine the sustainable use of the area in the future. More insight is needed in the potentials and limitations of alternative cropping practices to reduce current claims on land and water resources, and to meet the increasing demand for food.

The thesis addresses the two major development objectives in the CRV i.e. producing sufficient food for the increasing population, while at the same time ensuring efficient use of limited water and land resources under variable and changing climate conditions. The overall objective of this study was to identify and quantify crop intensification options under variable and changing climate conditions at field and river basin level in the CRV. The analysis combined empirical data and crop growth simulation at field scale and basin scale. The specific objectives were:

1. To quantify the historical impacts of climate change, land use change and irrigation water abstraction on the CRV water system (Chapter 2).
2. To analyse the current productivity, resource use efficiency and yield gaps of maize and wheat production across different farming zones in the CRV (Chapter 3).
3. To explore sustainable crop intensification options at field level to narrow the yield gap and analyse trade-offs with the water balance (Chapter 4).
4. To scale up the promising crop intensification options that increased productivity at maximum WUE and gross margin. Scaling up was done from field level to basin level with water use and food production calculated and mapped for several scenarios of targeted food production (Chapter 5).

In order to better understand the challenges related to water resources, the thesis first focused on the analysis of historical climate records (mainly rainfall, temperature and the associated evapotranspiration); land use change and the associated basin wide runoff change; and the effects of increased irrigation water abstraction on the CRV water system (Chapter 2). The results showed that temperature increased significantly whereas rainfall did not change between 1975 and 2008. The increase in temperature resulted in increased evapotranspiration that consumed an estimated 205 $Mm^3\ yr^{-1}$ more water of lakes and land surface in 2007 compared to 1990. Land use in CRV changed mainly due to expansion of cultivated land that caused net runoff to increase by 260 $Mm^3\ yr^{-1}$ between 1990 and 2007. Furthermore, irrigation water abstraction increased from ca. 20 to 285 $Mm^3\ yr^{-1}$ between 2002 and 2009. It is very likely that the combined effects of these developments have affected the terminal Lake Abyata, whose water level decreased with an average rate of about 0.165 m yr^{-1} since 1975. The present depth already forms a real ecological threat.

Chapter 2 shows that the scope for further expansion of farmland to increase food production is very limited in the CRV as about 70% of the land is already cultivated. More than two thirds of the remaining non-cultivated land is comprised of lakes, built-up land, marshland, exposed surfaces and afro-alpine vegetation, which are not suitable for agriculture, while one third is mainly forest and shrub land, predominantly in hilly areas. Therefore, intensification of crop production per unit of land is an important strategy to produce more food in the CRV. For understanding the prospects of intensification, this study brought together and analysed a large amount of data from farmers' fields and experiments, and used these empirical data to analyse the yield gaps and resource use efficiency across homogeneous farming zones in the CRV (Chapter 3). The average (2004-2009) yield gap of maize and wheat for rainfed conditions ranged between 4.2-9.2 t ha^{-1}, and 2.5-4.7 t ha^{-1}, respectively, across farming zones. These large gaps indicate a promising potential to increase food production, and call for the need to explore location-specific intensification options to realize yield gap closure.

In Chapter 4 crop intensification options were quantified by combining various levels of nitrogen fertilization, varieties, plant densities and residue covers across prevailing soils and climates in the CRV. The model-based exploration was done for maize and wheat at field scale using the process-based Agricultural Production System sIMulator (APSIM) model under historical climate (over 21 years) and future climate (in 2050s) conditions. Trade-offs were identified between crop yield and water use at various intensification levels. Climate change was projected to lower water-limited potential yield of maize and wheat by ca. 15-25% and 2-30%, respectively, compared to current climate conditions. Future increases in temperature would decrease the length of the growing period, and would result in decreased drainage and higher soil evaporation across all variety, location and management combinations for both crops. Variety selection and N fertilization were found to be more important factors contributing to yield gap closure than crop residue management and planting density and the magnitude of their effect depended on soil type and climate. There was a trade-off between intensification and water use through evapotranspiration, as increasing yield comes at the cost of increased transpiration. However, this trade-off can be minimized by choosing location-specific N levels at which both WUE and gross margin are maximised. These application rates varied between 75 and 250 kg N ha^{-1} across locations and soils, and allowed producing 80% of the water-limited potential yield (Yw) of maize and wheat.

In Chapter 5 promising intensification options at field level were analysed for their effect on the water balance at basin level. A spatial modelling framework for gridded simulation of yield and water balance components from cultivated land was set up with as major components high resolution (1 x 1km) gridded soil data, management variants and 21 years of climate data. APSIM was used as the crop growth model. The framework allowed designing various regional land use scenarios based on a spatially explicit optimization of water use efficiency (WUE) and gross margin, for which the consequences on food production and water use at basin level were evaluated. Results of the different land use scenarios demonstrated that crop intensification options for which WUE and gross margin are maximised can meet the projected food demand (year 2050) of the growing population in the CRV while at the same time saving large areas of the currently cultivated land. In the intensification scenarios total water loss through evapotranspiration from agricultural land is reduced compared with water loss from current cultivated land and low crop productivity levels. The results of Chapter 5 show that more sustainable use of land and water resources is possible while at the same time meeting the food demand of the growing population.

The study combined various data sources with inherent strengths and limitations (Chapter 6). Key findings in this thesis are a basis for further experimentation, for example, to verify identified yield gaps and to test in practice promising intensification options at representative soils, climate and farmers. Furthermore, implementation of promising intensification options in practice needs further identification and implementation of a proper mix of enabling socioeconomic, policy and institutional conditions.

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Writing the final words in the thesis is as difficult as writing any other section because it is difficult to find appropriate words strong enough to express the feelings I have to people that have contributed, and it is by no means possible to list all the names.

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Curriculum Vitae

Mezegebu Getnet Debas was born on the 25th of November 1973 in Gojjam, Ethiopia. Mezegebu has obtained his BSc degree in Soil and Water Conservation from Mekelle University in July 1999. In May 2000 he joined the then Ethiopian Agricultural Research Organization (EARO), now called the Ethiopian Institute of Agricultural Research (EIAR). He served as a junior researcher in the Agrometeorology research group up to July 2003. In August 2003, he continued his master's degree in agricultural meteorology at Punjab Agricultural University, India and graduated in July 2005. From August 2005 to August 2008, he served EIAR as a researcher in Agrometeorology.

In September 2008, Mezegebu obtained a PhD scholarship financed through the partnership program of the Dutch Ministry of Foreign Affairs/General Directorate for International Cooperation and Wageningen University and Research Centre as part of the project "Improving livelihood and resource management in Central Rift Valley of Ethiopia". He was admitted to the C.T. de Wit graduate school for Production Ecology and Resource Conservation at Wageningen University and did his PhD mainly at the Plant Production Systems Group. His PhD study focused on how to achieve simultaneously the two major development objectives in the Central Rift Valley of Ethiopia (CRV), i.e. sustainable use of land and water, and feeding the growing population under variable and changing climate. He combined empirical methods and detailed simulation modelling to diagnose and quantify problems related to the water balance and low land productivity in the CRV, and to explore sustainable intensification (SI) options while accounting for the trade-offs with water use at field scale. He scaled up the implications on production and basin wide water use to a regional scale using a gridded simulation approach.

He acquired basic skills in systems research approaches, particularly in application of detailed crop growth simulation at field scale, a gridded simulation approach at regional scale, climate analysis, data management and GIS techniques. Mezegebu is interested in research and teaching in the domains of agricultural systems, crop modelling, climate change adaptation and mitigation, and GIS in close collaboration with international research institutes.
He is currently working in Climate and Geo-spatial Research (CGR) of the EIAR.

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List of Publications

Journal article(s):

Getnet, M., Hengsdijk, H. & Van Ittersum, M. (2014). Disentangling the impacts of climate change, land use change and irrigation on the Central Rift Valley water system of Ethiopia. Agricultural Water Management, 137: 104-115.

Getnet, M., Martin van Ittersum, Huib Hengsdijk, Katrien Descheemaeker (2015). Yield gaps and resource use across farming zones in the Central Rift Valley of Ethiopia, Experimental Agriculture Journal, Cambridge

Getnet, M. (2005). Rainfall-Runoff Modeling Using Remote Sensing and GIS: USDA-SCS Method, Ethiopian Journal of Water Science and Technology, 9: 71-75

Girma M, **Getnet**, **M** Gizachew L and Takele M. Dinka (2013). Integration of information on climate, soil and cultivar to increase water productivity of maize in semi-arid eco-regions of Ethiopia, Ethiopian Journal of Agricultural Science, 14:123-139

Chapter in a book:

Habtamu Admassu, **Mezgebu Getinet**, Timothy S. Thomas, Michael Waithaka, and Miriam Kyotalimye (2013). Ethiopia; In: Michael Waithaka, Gerald C. Nelson, Timothy S. Thomas, and Miriam Kyotalimye (eds.) East African agriculture and climate change: a comprehensive analysis, International Food Policy Research Institute Washington, DC PP 402

Conference/Proceedings:

Getnet, M. (2007) Application of Remote Sensing and GIS in Overcoming the Challenges of Data Acquisition, Processing & Decision Making in Agriculture, Proceeding of National Research Symposium, Adama University

Girma M., Girma A., **Getnet, M.**., Gizachew L., Degefe T. and Daniel A., (2008) Agrometeorology and Geographic Information System to enhance coffee research and development, proceeding of the national workshop on four decades of coffee research and development in Ethiopia, Coffee diversity and knowledge, Addis Ababa (Ghion Hotel), Ethiopia.

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Getnet M, M van Ittersum, H Hengsdijk, K Descheemaeker (2015). Prospects of feeding more people under changing conditions of climate, land use and water resources in the Central Rift Valley (CRV), Ethiopia. Dreseden Nexus Conference, Germany; 25-27 March, 2015.

Poster presentations:

Getnet M., M. van Ittersum, K Descheemaeker, H Hengsdijk (2015). Feeding Ethiopia in changing context: from diagnosis to exploration of climate smart options, Climate Smart Agriculture conference, Montpellier, France; 16-18 March, 2015

Getnet, M., H Hengsdijk, H van Keulen, (2010). Analysis and exploration of resource management options: Central Rift Valley of Ethiopia: Wageningen UR, The Ethiopian-Wageningen UR 'Science for impact' workshop, 2010-07-07, Holetta, Ethiopia.

Getnet, M., H Hengsdijk, (2010). Spatial and temporal climate characteristics of the Central Rift Valley, Wageningen UR, The Ethiopian-Wageningen UR 'Science for impact' workshop, 2010-07-07: Holetta, Ethiopia

Policy Brief:

Habtamu Admassu, **Mezgebu Getinet**, Timothy S. Thomas, Michael Waithaka, Miriam Kyotalimye, 2012. East African Agriculture and Climate Change: A Comprehensive Analysis-Ethiopia, IFPRI,Washington DC, USA

PE&RC Training and Education Statement

With the training and education activities listed below the PhD candidate has complied with the requirements set by the C.T. de Wit Graduate School for Production Ecology and Resource Conservation (PE&RC) which comprises of a minimum total of 32 ECTS (= 22 weeks of activities)

Review of literature (6 ECTS)

- Multi-scale analysis and exploration of resource management options for the Central Rift Valley, Ethiopia

Writing of project proposal (4.5 ECTS)

- Multi-scale analysis and exploration of resource management options for the Central Rift Valley, Ethiopia

Post-graduate courses (5 ECTS)

- Integrated assessment of global environmental change: causes and responses; SENSE (2008)
- Integrated assessment of agriculture and sustainable development; SEAMLESS (2008)

Deficiency, refresh, brush-up courses (6 ECTS)

- Quantitative analysis of land use systems; Plant Production System (2009)

Competence strengthening / skills courses (3.6 ECTS)

- Scientific publishing; PE&RC (2008)
- Interpersonal communication for PhD students; WGS (2008)
- Techniques of writing and presenting scientific papers; PE&RC (2014)
- Project and time management; PE&RC (2014)

PE&RC Annual meetings, seminars and the PE&RC weekend (1.8 ECTS)

- 40 Years theory and model at Wageningen UR (2008)
- PE&RC Weekend (2008)
- PE&RC Day: accelerate scientific progress: expect the unexpected (2008)
- SENS/EPCEM Symposium (2008)

Discussion groups / local seminars / other scientific meetings (11.1 ECTS)

- Quarterly scientific meetings of Agrometeorology and GIS research; Ethiopian Institute of Agricultural Research (2009-2014)

- Project review meetings; Ethiopian Institute of Agricultural Research (2009-2014)
- First year anniversary workshop of Ethiopia-WUR collaboration program on science for impact; Holeta Agricultural Research Centre, Ethiopia (2010)
- Climate downscaling using RegCM4; Adama, Ethiopia (2011)
- Climate and agriculture: exploring the online databases; climate explorer and NASA power; Melkassa Ethiopia (2012)
- GIS training for users; IFPRI/EDRI, Ethiopia (2013)
- Project planning meeting on climate smart agriculture; Addis Ababa, Ethiopia (2013)
- Stakeholders meetings on monitoring and evaluation of external funded climate adaptation projects; Addis Ababa, Ethiopia (2013)
- Consultative meeting and training workshop on APSIM model with Australian partners and model developers; Melkassa, Ethiopia (2013)
- Global yield gap Atlas workshop; Addis Ababa, Ethiopia (2014)
- Sustainable Intensification of Agricultural Systems (SIAS) (2014-2015)

International symposia, workshops and conferences (2.9 ECTS)

- Climate Smart Agriculture conference; Montpellier, France (2015)
- The Nexus conference: global change, sustainable development goals and the nexus approach; Dresden, Germany (2015)

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