Rainwater harvesting for dryland agriculture in the Rift Valley of Ethiopia

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Chapter 1

Introduction

Introduction

1.1 The challenge of agricultural production in Ethiopia

The great challenge for the coming decades will be the task of increasing food production to ensure food security for the steadily growing world population, particularly for societies hosted in environmentally vulnerable areas such as sub-Saharan Africa (ICSU, 2002). In sub-Saharan Africa (SSA), human population grows by 3% a year while yields of the major food crops grow only at 1% a year implying a declining per-capita food production (Dyson, 1999; Rockström, 2003; Sachs et al., 2004). More than 41% of the population in Africa lives in drylands that cover about 43% of the continent (UNDP, 1997). In drylands, water is a key challenge for food production due to the extreme variability of rainfall, long dry seasons, and recurrent droughts and dry spells. Most hungry and poor people live in regions where water challenges pose a particular constraint to food production (Koohafkan and Stewart, 2008). Rainfall variability in Africa is twice that of temperate regions, which makes agricultural drought more frequent in Africa than anywhere else in the world (World Bank, 2004). Droughts have mainly affected the horn of Africa and the Sahel regions (IPCC, 2007; L'Hôte et al., 2002) although it occurs in all drylands of SSA.

In Ethiopia, agriculture is the mainstay of the economy contributing the largest share to GDP, export trade and earnings, and employs 84% of the population (Teshome, 2006). Yet, agriculture is the most volatile sector mainly due to its dependence on rainfed systems (close to 97% of the agricultural land is rainfed) and the seasonal shocks that are frequently observed (Awulachew et al., 2005). In association with the burgeoning population, the fresh water availability per capita in the country will be less than 1000 m^3 per person per year by 2050 putting it as one of the water scarce countries (Fischer and Heilig, 1997; Wallace, 2000). Apart from that, the arid, semiarid and dry sub-humid lands of Ethiopia occupy approximately 65% of the total land mass (close to 700,000 km^2) of the country (EPA, 1998) and 46% of the total arable land (Yonas, 2001). Particularly, semi-arid areas cover 301,500 km^2 (27 % of the country) and represent the crop production zone suffering from a serious moisture stress (Engida, 2000).

The seasonal and annual rainfalls in Ethiopia are highly unpredictable and variable with more risk of crop failure in arid and semi-arid regions due to less water availability during the growing seasons (Gissila et al*.,* 2004; Tesfaye and Walker, 2004). Production of major cereals (*tef*, barley, wheat, maize, sorghum and millet) showed statistically significant correlations with seasonal rainfall variability in the Amhara region of Ethiopia during 1994-2003 (Bewket, 2009). Given that Ethiopia's national GDP is mainly based on rainfed agriculture, annual GDP growth during 1983-2000 was correlated with annual rainfall variation (World Bank, 2006)**.**

In addition to unpredictability and unreliability of annual and seasonal rainfalls, the loss of rainwater through non-productive pathways also contributes significantly to water scarcity in rainfed agriculture. As much as 10 – 40% of the rainfall can be lost to surface runoff (Araya and Stroosnijder, 2010; Wolderufael et al., 2008). Soil evaporation may reach 50% of the rainfall in dryland regions (Daamen et al., 1995; Rockström et al., 1998; Stroosnijder and Hoogmoed, 1984). Hence, the fraction of rainfall used for plant transpiration can be as low as 15% of the terrestrial rainfall in drylands (Stroosnijder, 2009). Deteriorated dryland soils have low infiltration and water holding capacity, shallow depths and are sensitive to crusting (Hoogmoed, 1999). In Ethiopia, because of incomplete ploughing by the traditional *Maresha* ard implement, the farmers have to do repeated tillage practices before sowing of cereal crops, thus the soil is excessively pulverised (Temesgen, 2007). This results in a poor soil structure, which decreases rainfall infiltration and enhances surface runoff generation.

To keep in pace with the demand for food for the increasing population, the Ethiopian drylands should be made more productive through appropriate rainwater harvesting and management techniques (Abdu and Schultz, 2005; Temesgen, 2007; Welderufael et al., 2008). There is a need to develop techniques that minimize the non-productive losses of rainwater thus enhancing the productive green water flow through transpiration.

1.2 Rainwater harvesting and management for dryland agriculture

In rainfed areas, the additional amount of water needed to support agriculture directly depends on gains in water productivity - "more crop per drop" - through efficient water management techniques (IWMI, 2000; Molden et al., 2010; Oweis and Hachum, 2006). By improving the water productivity, the current water requirement for food of 1300 m^3 cap^{-1} yr^{-1} may be reduced to 1000 m^3 cap^{-1} yr^{-1} by 2050 thus substantially reducing the water deficit in water scarce countries (Rockström and Barron, 2007). Hence, it has been suggested that future water demand for food requires a focus on 'green water' management in rainfed areas instead of 'blue water' for irrigation (Falkenmark and Rockström, 2004). The 'green water' is defined as the fraction of rain water that infiltrates into the rooted soil zone and that is used through the process of transpiration for biomass production (Ringersma, 2003; Stroosnijder, 2003). The 'blue water' represents water in the rivers, aquifers, lakes, and reservoirs (Falkenmark and Rockström, 2006). Based on a modelling study on water management for rainfed agriculture, a 25% reduction in evaporation (vapour shift) and a 25% collection of surface runoff suggests that global crop production can be increased by 19%, which is comparable with the 17% effect of current irrigation (Rost et al., 2009). Apart from this, the cost of upgrading rainfed agriculture through appropriate rainwater management is by far lower than that of constructing irrigation schemes without even accounting for the social and environmental problems of irrigation (De Fraiture et al., 2007).

Improving water use efficiency in arid, semi-arid and dry sub-humid areas can be achieved either by increasing the amount of water available for transpiration and/or by increasing the efficiency with which transpired water produces more biomass (Wallace, 2000). There are two broad strategies for increasing yields in rainfed agriculture when water availability in the root zone constrains crop growth: (1) capturing more water and allowing it to infiltrate into the root zone; and (2) using the available water more efficiently (increasing water productivity) by increasing the plant water uptake capacity and/or reducing non-productive soil evaporation (Rockström et al., 2010). In arid regions, water harvesting can increase the beneficial water available for transpiration from 20% to 50% (Oweis et al., 1999). Although nutrient limitations set stronger ceilings on yield than water availability in many dryland regions (Breman et al., 2001; Molden et al., 2010), investments in soil nutrients and related production enhancing inputs are less likely due to risks of crop failure by erratic rainfall and long dry spells (Bindraban et al., 1999; Dercon and Christiaensen, 2011; Rockström et al., 2002). Hence, lowering these risks through investments in appropriate rainwater harvesting and management techniques can bridge the gap between dry spells and farmers' attitudes regarding agricultural investments (Rockström et al., 2010). Integrated water and soil management – particularly focused on soil tillage for improved infiltration, water harvesting for dry-spell mitigation and soil fertility improvement – can substantially improve yields and water productivity (Falkenmark and Rockström, 2004).

Rainwater harvesting either through runoff collection from a catchment area upslope or through conservation of rainfall where it falls in the cropped area or pasture has received increasing attention in rainfed systems of the SSA (Motsi et al., 2004; Ngigi, 2003; WOCAT, 2007). Conservation farming with improved and non-inversion tillage systems (sub-soiling, ripping, etc.) has got increasing attention (FAO, 2005; Liniger et al., 2011; Rockström et al., 2009). The claimed benefits of conservation tillage encompass improved infiltration, reduced soil erosion, and better carbon sequestration through the organic matter accumulated in the soil from the crop residues and cover crops (Ito et al., 2007; Rockström, 2009). However, only few studies have been undertaken to understand the effect of conservation farming and improved tillage techniques as *in situ* moisture conservation in dryland agricultural systems of the SSA (Enfors et al., 2011; Temesgen, 2007). Owing to its simplicity and low investment costs, the development of *in situ* rainwater harvesting and management techniques could be viable amongst the smallholder rainfed systems. Hence, further research is needed to improve the indigenous practices and further develop new appropriate *in situ* rainwater harvesting and management techniques.

Given the considerable spatial and temporal variation in crop responses to climate variability, localised, community-based efforts are supposed to be effective to increase local adaptive capacity, take advantage of changes that may lead to increased crop and livestock productivity where this is possible, and to buffer the situations where increased stresses are likely (Thornton et al., 2010). Because the probable increases in runoff generally occur during high flow seasons, and may not alleviate dry season problems, the extra water should be stored during the wet seasons and utilised during dry spells or the dry season (Arnell, 2004). Apart from that, small-scale rainwater harvesting and management technologies are important to address environmental problems such as soil erosion and flooding (Li et al., 2000). A historical review of human responses to climatic variability also indicated that there has been a correlation between heightened historical human efforts for construction of rainwater harvesting structures across regions in response to abrupt climate fluctuations, like aridity and drought (Pandey et al., 2003). Rainwater harvesting in response to climate extremes can enhance the resilience of human society. Lessons from the past show that farmers in many rural areas have traditionally evolved and adapted to ever-changing environments by developing diverse and resilient farming systems in response to different opportunities and constraints faced over time (Altieri and Koohafkan, 2008).

Despite the previous efforts on planning and implementation of newly introduced rainwater harvesting and management techniques, there has been minimal adoption by smallholder farmers (Abera, 2004; Amsalu and De Graaff, 2006; MoA, 2001). The limited participation of the smallholders in the process resulted in underutilization of the people's own experience and potential to create new knowledge for further development (Ncube et al., 2008; Spaan, 2003). Moreover, closer examination of the real agro-climatic determinants for crop production is crucial for an appropriate planning of rainwater harvesting techniques (Araya, 2011; Barron, 2004). Farmer participatory research can be an effective way of exploiting the existing knowledge and experiences (Velduizen et al., 2002). It is, therefore, hypothesized that the indigenous knowledge of the smallholder farmers in the Ethiopian drylands could be instrumental not only to discover the real causes of agricultural water scarcity but also to guide the future directions of research and development for improved agricultural water management in this drought-prone region.

1.3 Objective and research questions

The Ethiopian Rift Valley, which covers a huge proportion of the vast drylands, is under increasing land-use conversion from pastoral to mixed farming system (Dessie and Kleman, 2006; Garedew et al., 2009; Tsegaye et al., 2010). Following conversion of natural vegetation and grasslands into cultivated fields, the incorporation of crop residues with tillage and repeated exposure of the soil to the atmosphere causes loss of organic matter through oxidation and mineralization in the Central Rift Valley of Ethiopia (Lemenih et al., 2005; Temesgen, 2007). In the Central Rift Valley areas, the seasonal rainfalls are highly unpredictable and variable with higher risks of crop failure and low productivity due to less water availability during the growing seasons (Tesfaye and Walker, 2004; Tilahun, 2006).

Therefore, the general objective of this study was to evaluate and develop appropriate rainwater harvesting and management techniques for the Central Rift Valley of Ethiopia.

The following research questions were addressed in this study.

1) What are the common rainwater harvesting and management techniques in drought-prone sub-Saharan Africa, and how have they performed? (*Chapter 2*)
2) How does drought vulnerability determine the dynamics of land-use/cover and development of better land management techniques? (*Chapter 3*)
3) What are the long-term implications of the conventional *Maresha* ploughing on soil water properties in the Rift Valley drylands of Ethiopia? (*Chapter 4*)
4) Can the FAO's AquaCrop model be used to examine the effect of rainwater harvesting techniques on crop yields in response to different rainfall patterns? (*Chapter 5*)
5) What is the most appropriate approach to stimulate adoption of RWHM measures in the current farming system of the CRV drylands? (*Chapter 6*)

1.4 Description of the study area

The Ethiopian Rift Valley is part of the East African Rift System and covers the major dryland portion of the country. It divides the Ethiopian highlands into two, the eastern and western escarpments. Ayenew (2007) further divided the Ethiopian Rift Valley into four sub-systems: 1) the southern part around Lake Turkana, 2) the Chew Bahir area, 3) the Central Rift Valley and 4) the Northern Rift Valley which encompasses the Afar depression.

The study area is situated in the Central Rift Valley (CRV), at about 190 km south of Addis Ababa. It is located between latitudes 7^0 30' and 7^0 40' N along a strip bounded by Lake Langano to the east and Lakes Abijata and Shala to the west (Fig 1.1). During November to February, long periods of dry weather are experienced, with little or no rainfall except episodic events in January and low relative humidity. Between March and May the weather in this area becomes more unsettled and the rains at this season are light and unreliable sharing about 23% of the annual amounts. The main rains in the study area occur between June and September which accounts about 68% of the total annual amounts. The annual rainfall in the area varies between 300 and 1000 mm with an average value of about 655mm. The rainfall variability between years (CV = 30%) and distribution within a year is more important than the total seasonal values as far as agricultural production in the area is concerned.

The geological and geomorphologic features of the region are the results of volcanic and sedimentation processes (Ayenew, 2007). The volcanic products were mainly fissural basaltic lava flows, stacked one over the other, alternating with volcano-classic deposits derived from tuff, ignimbrite and volcanic ash (Ayenew, 2007). The basalt extrusions were interspersed with large accumulations of rhyolite and trachyte, breccias, ignimbrite and related shallow intrusions (Kazmin, 1979). The area has an average slope of 0-3% with an altitude of about 1600 m. The soil is classified as Haplic Solonetz with a texture ranging from loamy sand to sandy loam (Itanna, 2005). As nutrients appeared largely associated with the organic matter (directly and through the CEC), being conserved by the internal cycling in the natural vegetation dominated by acacia woodlands, the ongoing destruction for more cultivated lands is leading to a significant decline in soil fertility (Fritzsche et al., 2007; Lemenih et al., 2005).

Although the area was previously covered by dense acacia woodlands consisting of four main acacia species (*Acacia tortilis*, *Acacia senegal, Acacia seyal* and *Acacia etbaica)* and used by the pastoral Oromo people, the woodlands have been steadily converted to a sedentary and subsistent mixed farming system (Argaw et al., 1999; Eshete, 1999). The major types of crops produced in the area are maize and haricot bean. Livestock production, which is still one of the main components of farmers' occupation, is present throughout the area and includes mainly goats and cattle keeping.

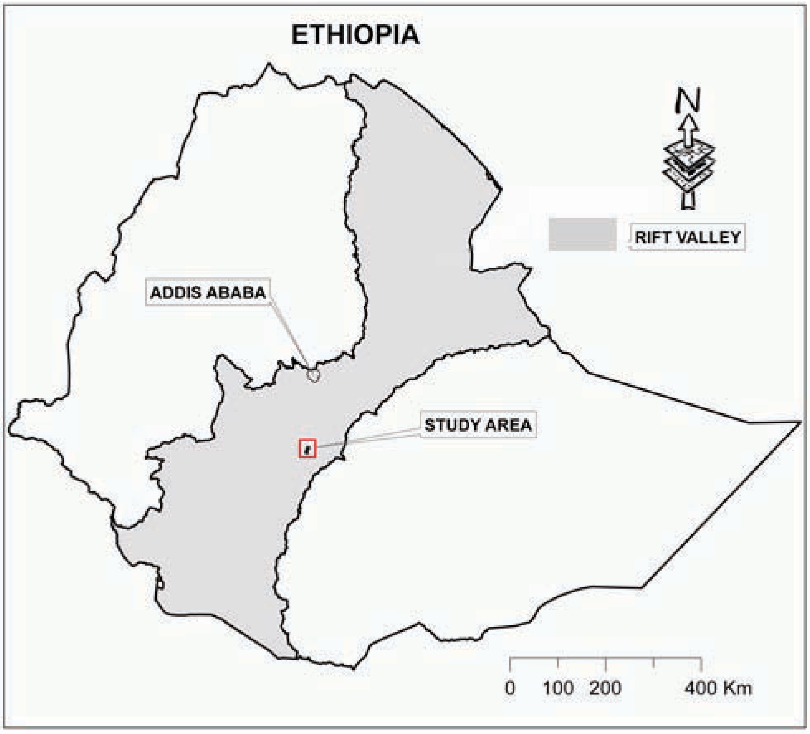

Figure 1.1. Location map of the study area in the Rift Valley drylands of Ethiopia.

1.5 Thesis outline

The research objectives defined in section 1.3 are addressed in chapters 2 to 6 all of which are independent and stand-alone. Chapter 2 presents an overview of the various rainwater harvesting and management techniques in sub-Saharan Africa, and examines the biophysical and socioeconomic performances. This chapter enables exploration of the best experiences and most appropriate techniques that could possibly be introduced to the Central Rift Valley drylands of Ethiopia.

Chapters 3 addresses the changing trends in land-use and land management and evolving rainwater harvesting and management techniques. The effect of drought vulnerability in the trends of changes in land-use and land management was determined. The interplay of recurrent drought with other institutional and socioeconomic factors to drive land-use changes is explained. Moreover, the indigenous techniques of rainwater harvesting and knowledge gaps for further improvements are identified.

Chapter 4 analyses the effect of land-use conversion from woodlands to crop cultivation and long-term tillage with traditional *Maresha* plough on soil water properties. The dynamics of infiltration and soil evaporation with long-term tillage after land-use conversion are examined.

Chapter 5 presents the role of the FAO's AquaCrop model in simulating the effect of rainwater harvesting techniques in response to different rainfall patterns and soil fertility levels in the CRV of Ethiopia. After calibration of some input parameters and validation based on field experimental data, the possibility of applying the model as an important tool in a participatory rainwater harvesting and management planning approach is implied.

Chapter 6 addresses the possibility of merging the indigenous knowledge of rainwater harvesting with experiences from elsewhere and the role of scientific information to fill knowledge gaps for improved and sustained agricultural production. Hence, a new approach of participatory rainwater harvesting and management planning is presented.

Chapter 7 presents a synthesis on the major finding of this study and the possible contributions to the scientific efforts of developing appropriate rainwater harvesting and management technologies for improved and sustainable agricultural development. The implications and recommendations of this study are also presented.

Chapter 2

Rainwater harvesting and management in rainfed agricultural systems in sub-Saharan Africa – A review

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Rainwater harvesting and management in rainfed agricultural systems in sub-Saharan Africa – A review

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Abstract

Agricultural water scarcity in the predominantly rainfed agricultural system of sub-Saharan Africa (SSA) is more related to the variability of rainfall and excessive non-productive losses, than the total annual precipitation in the growing season. Less than 15% of the terrestrial precipitation takes the form of productive 'green' transpiration. Hence, rainwater harvesting and management (RWHM) technologies hold a significant potential for improving rainwater-use efficiency and sustaining rainfed agriculture in the region. This paper outlines the various RWHM techniques being practiced in SSA, and reviews recent research results on the performance of selected practices. So far, micro-catchment and *in-situ* rainwater harvesting techniques are more common than rainwater irrigation techniques from macro-catchment systems. Depending on rainfall patterns and local soil characteristics, appropriate application of in-situ and micro-catchment techniques could improve the soil water content of the rooting zone by up to 30%. Up to sixfold crop yields have been obtained through combinations of rainwater harvesting and fertiliser use, as compared to traditional practices. Supplemental irrigation of rainfed agriculture through rainwater harvesting not only reduces the risk of total crop failure due to dry spells, but also substantially improves water and crop productivity. Depending on the type of crop and the seasonal rainfall pattern, the application of RWHM techniques makes net profits more possible, compared to the meagre profit or net loss of existing systems. Implementation of rainwater harvesting may allow cereal-based smallholder farmers to shift to diversified crops, hence improving household food security, dietary status, and economic return. The much needed green revolution and adaptations to climate change in SSA should blend rainwater harvesting ideals with agronomic principles. More efforts are needed to improve the indigenous practices, and to disseminate best practices on a wider scale.

2.1 Introduction

Subsistence rainfed agriculture is the mainstay of most African economies, and contributes 10–70% to their GDP. African agriculture, however, has the lowest rate of productivity increase in the world. Africa was the only major region with a decline in food production *per capita* in the years 1980–2000 (Sachs et al., 2004). In sub-Saharan Africa (SSA), 95% of the cultivated land is under rainfed agriculture, and an estimated 41% of the region's population (*ca.* 260 million) lives in drought-prone dry lands (Svendsen et al., 2009; UNCCD, 2009). SSA has less than 2% of the world's total irrigated land (Field, 1990). Apart from the physical water scarcity, irrigation is unaffordable in SSA, as direct investment costs alone can reach US$ 8,300 ha^{-1} (FAO, 1992), and increase to US$ 18,000 ha^{-1} when indirect infrastructural costs are included (Rosegrant, 1997). Hence, for the near future, rainfed agriculture will be the dominant source of food for the region's burgeoning population.

However, water supplies in Africa are shrinking and highly variable. Concurrent with a huge population increase during 1970–1994, a 2.8 times reduction in human water supply took place in Africa while the reduction in Europe was 16% (Shiklomanov, 2000). Year-to-year variability of renewable water resources is also high in arid and semi-arid regions where actual availability is limited. It has been estimated that in dryland regions, there could be 150-200% less renewable water resources in individual years than the long-term average, whereas in wet regions this difference is in the range of just 15–25% (Shiklomanov, 1998).

In addition to the scarcity and unreliability of annual rainfall, the loss of rainwater through non-productive pathways also seriously limits rainfed agriculture in SSA. Soil evaporation may reach 50% of the rainfall (Daamen et al., 1995; Rockström et al., 1998; Stroosnijder and Hoogmoed, 1984). As much as 10-30% of the rainfall can be lost to surface runoff (Araya and Stroosnijder, 2010; Welderufael et al., 2008). Depending on the rainfall pattern, drainage can claim 10–30% of the rainfall (Klaij and Vachaud, 1992). Accordingly, more than 50% of the rainfall in dryland cropping systems may be lost non-productively. Stroosnijder (2009) argued that the fraction of rain used for plant transpiration can be as low as 15% of the terrestrial rainfall in SSA. In a worst case scenario, as in the Sahel region of Niger, only 4–9% of the rainfall takes the productive water-flow path as 'green' transpiration under a non-fertilised crop (Rockström et al., 1998).

Africa's dependence on rainfed agriculture means that it is susceptible to climatic variability which can severely affect food production and, therefore, human security and export revenues. Based on the assessment of vulnerabilities and risks of climate change in Kenya, Malawi and Ethiopia, climate-change emission scenarios revealed more extreme events in the future that could destabilise development activities (UNDP, 2007). River catchments are also sensitive to changes in regional climate which can be exacerbated by anthropogenic influences. For instance, with a 2°C climate warming and a 10% reduction in precipitation, a 150–200% decrease in water resources is possible for regions located in the arid climate zones (Shiklomanov, 1998).

In eastern Africa, grain yields and growth in the overall agricultural gross domestic product depend heavily on the annual precipitation (UNDP, 2007). Farmers in semi-arid East Africa prioritise drought as their major productivity-reducing problem, while scientists identify soil degradation as a major threat (Slegers, 2008). In north-eastern Ethiopia, for example, drought-induced losses in crops and livestock between 1998 and 2000 were estimated at US$ 266 per household - greater than the annual average cash income for more than 75% of households in the region (Carter et al., 2004). In drylands, where water is even more limiting than land, improvement of agricultural water productivity ('more yield per drop') has been identified as a vital strategy. Satisfaction of the increased demand for food, water and material goods by a growing population, while at the same time protecting the ecological services of water, requires increased efforts towards doubling water productivity (Postel, 2000; Rockström, 2003).

Three-quarters of the additional food that the global population needs over the next several decades could be met by bringing the production level of the world's low-yield farmers up to 80% of that which high-yield farmers obtain from comparable lands (CAWMA, 2007). The greatest potential increases in yield are in rainfed areas, where many of the world's poorest rural people live, and where the management of water is the key to such increases (CAWMA, 2007). In SSA, there is no hydrological limitation to doubling the staple food production of the smallholder-based rainfed agriculture through better soil and water management techniques (Rockström et al., 2002). Rainwater harvesting is a growing technique to significantly increase water productivity, thus mitigating agricultural water scarcity and allowing increases in crop production levels. Multitudes of indigenous and recently developed rainwater harvesting techniques are used in different parts of SSA. Some of these indigenous techniques have been introduced and are being widely applied in the drylands of western Asia (Oweis et al., 2004). The techniques and modes of application, however, differ regionally. The best experiences in one country have the potential to be adapted in another country which has similar problems of water scarcity. To convince and attract more development partners and avoid scepticism about the significance of the technology in SSA, an overview of the contemporary research findings on the best experiences with rainwater harvesting is essential. Oweis and Hachum (2006) outlined the most important water-harvesting practices and their field performance for Western Asia and North Africa, but no such review exists for SSA. Therefore, the aim of this paper is to present a review of commonly applied RWHM practices in SSA, and report the current research findings concerning their biophysical and socioeconomic performance.

2.2 Scope and overview of rainwater harvesting and management techniques in SSA

In the past, the broad term 'water harvesting' has been used more frequently than 'rainwater harvesting' (Boers, 1994; Myers, 1975). Many authors have defined water harvesting and rainwater harvesting interchangeably, as 'the collection and storage of any form of water either from runoff or creek flow for irrigation use' (Boers and Ben-Asher, 1982; Critchley and Siegert, 1991; Falkenmark et al., 2001; Nasr, 1999; Oweis et al., 1999; Siegert, 1994). Although the ancient practices were primarily designed to meet domestic water needs, gradually the technologies also came to be used for agricultural purposes. In recent decades, scientists in SSA, the Middle East and Southeast Asia have made efforts to develop and test a wide variety of techniques for collecting, storing, and using natural precipitation for agricultural purposes (Humphreys and Bayot, 2009; Oweis et al., 2004; Rockström et al., 2002). Agricultural uses include the supplemental irrigation of crops, the provision of water for livestock, fodder and tree production and, less frequently, water supply for fish and duck ponds. Recently, the concept has been extended to encompass *in-situ* techniques and appropriate land management practices which enhance infiltration and reduce surface runoff and soil evaporation (Rockström et al., 2002; Temesgen, 2007).

In the present paper, the more comprehensive and contemporary term 'rainwater harvesting and management' (RWHM) is used to encompass all practices of rainwater collection, storage and efficient utilisation for crop production (Ngigi et al., 2005; Rockström et al., 2002). RWHM practices being employed in SSA are discussed in four categories: (I) Collection of surface runoff from micro-catchment systems with water storage in the soil for dry-spell mitigation, (II) Collection of surface runoff from macro-catchment systems with water storage for supplementary irrigation, (III) Techniques for maximising infiltration, reducing surface runoff and soil evaporation, and improving soil water availability, (IV) Techniques for maximising plant water uptake and response farming.

2.2.1 Micro-catchment systems with water storage in the soil for dry spell mitigation

Micro-catchment rainwater harvesting systems are designed to collect runoff from a relatively small catchment area, mostly 10–500 m^2, within the farm boundary. The runoff water is usually guided into a type of infiltration enhancement structure and used to grow plants (Figure 2.1). The ratio of the collection catchment to the cultivated target area can vary between 2:1–10:1 (Desta, 2007; FAO, 1991; Liniger et al., 2011). Unlike the macro-catchment systems, the catchment area can be easily controlled by the farmer which makes the systems easy to adapt and replicate.

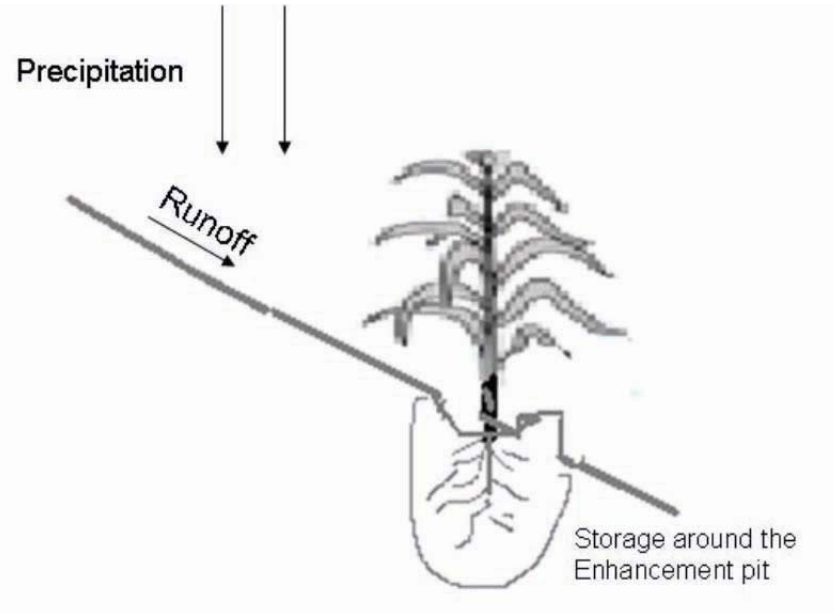

Figure 2.1. Typical example of micro-catchment rainwater harvesting systems.

Table 2.1. Micro-catchment rainwater harvesting - Overview of the most commonly practised systems in sub-Saharan Africa.

Type of the micro-catchment systems	Description	Countries of wider application	References
Pitting (*Zai* pits, *Ngoro* pits, trenches, *tassa* pits, etc)	*Zai* pits: A grid of planting pits is dug across plots that could be less permeable or rock-hard; organic matter is sometimes added to the bottom of the pits; *Ngoro* pits: A series of regular traditional pits, 1.5m square by 0.1–0.5m deep with the crops grown on the ridges around the pits; Trenches: pits are made along the contour sometimes with a bund downslope either staggered or continuous to check the velocity of runoff, conserve moisture and increase ground water recharge.	West Africa (Burkina Faso, Mali, Niger). East Africa (Tanzania, Kenya, Somalia, Uganda, Ethiopia). Southern Africa (Zimbabwe, South Africa)	Malley et al. (2004); Mupangwa et al. (2006); Reij (1996); WOCAT (2010)
Contouring (Stone/soil bunds, hedge-rows, vegetation barriers)	Stone and soil bunds: A stone or sometimes earthen bank of 0.50–0.75 cm height is piled on a foundation along the contour in a cultivated hill-slope, sometimes stabilised with grasses or other fodder plant species; Hedge rows: Within individual cropland plots, strips of land are marked out on the contour and left unploughed in order to form permanent, cross-slope barriers of naturally established grasses and herbs. Alternatively. Shrubs are planted along the contour.	East Africa (Kenya, Ethiopia, Tanzania). West Africa (Burkina Faso). South Africa.	Kiepe (1995a); Spaan (2003); WOCAT (2010)
Terracing (*Fanya Juu*, Semi-circular and hillside terraces)	Bunds in association with a ditch, along the contour or on a gentle lateral gradient are constructed in different forms. The *Fanya Juu* terraces are different from many other terrace types in that the embankment is put in the upslope position.	East Africa (Kenya, Ethiopia, Tanzania).	Tengberg et al. (1998); WOCAT (2010)
Micro-basins (Negarims, half-moons, and eye-brows)	Different shapes of small basins, surrounded by low earth bunds are formed to enable the runoff to infiltrate at the lowest point, where the plants are grown. The differences between the different structures is basically in their shapes, Negarims (diamond), Halfmoons (Semi-circular), etc.	East Africa (Ethiopia, Kenya, Tanzania, Uganda). West Africa (Burkina Faso, Mali, Niger).	Abdulkedir and Schultz (2005); FAO (1991); Spaan (2003)

The most commonly applied micro-catchment rainwater harvesting techniques in SSA include pitting, contouring, terracing and micro-basins (Table 2.1). Some of the techniques may have different names in different regions, and minor differences in design and use. *Zai* pits have been used in Burkina Faso for many years (Reij, 1996; Slingerland and Stork, 2000). Pits are dug 60×60 cm apart; and three to four grains of sorghum are planted in each pit (WOCAT, 2007). A similar type of pitting, the *ngoro* system, is used in steep (20–50%) sloping areas of Tanzania (Malley et al., 2004). In Niger, the traditional *tassa* system of cropping is employed by digging small planting holes of 20–30 cm diameter and 20–25 cm depth about 1 m apart in each direction, to hold pockets of rainwater and moisten the soil (Baidu-Forson, 1999; Kabore and Reij, 2004). The combination of planting pits (*tassa*) with stone lines is used to rehabilitate degraded and crusted lands and bring them into cultivation (WOCAT, 2007). In response to sand encroachment on top of fertile soils, the planting of seedlings in shallow pits (5–15 cm deep and 10–30 cm wide) at intervals of 40–70 cm (*Magun cultivation*) has recently been adopted in semi-arid regions of Sudan (Ousman-Elasha et al., 2006).

Micro-catchment water harvesting techniques that are being promoted throughout southern Zimbabwe include dead-level contours with or without infiltration pits, graded contour ridges (< 5% slope) and *fanya juu terraces* (Kahinda et al., 2007; Mupangwa et al., 2006). In the field, the dead-level contours harness water originating from the area upslope. Planting pits (15×15×15 cm dimensions) are dug in September or October in the same positions annually, to collect rainwater in October and November before planting takes place in December (Mupangwa et al., 2006). Contour ridges vary in size, the smallest having cross-sectional dimensions of 1.5 m width and 0.5 m depth (Mupangwa et al., 2006). The basin and mulch technique is an innovative water-conservation technique used in South Africa to reduce total runoff to zero and soil evaporation considerably, thus improving crop yields (Bennie and Hensley, 2001; Botha et al., 2007). The *teras* system in Sudan, consisting of a field surrounded on three sides by low earth bunds, while the upstream side functions as an inlet for surface runoff, has been practiced for centuries (Niemeijer, 1998). Runoff harvesting on clay soils by constructing earth bunds (*trus* cultivation) was first used in 1964 and has also become common in the Darfur area of Sudan (Ousman-Elasha et al., 2006). As rain-fed farming on sandy soils has become increasingly risky, indigenous *trus* cultivation has proved important in recent years. Soil and stone bunds, micro-basins, different types of terrace and trenches are some of the soil and water conservation practices in arid and semi-arid Ethiopia that are also used as micro-catchment rainwater harvesting systems (WOCAT, 2010). These techniques are commonly applied in areas characterised by low and erratic rainfall, and farming systems dominated by seasonal cereal crops such as maize (*Zea mays),* beans (*Vicia faba* L), pepper *(Capsicum annuum)* and tef (*Eragrostis tef*). The semi-circular terraces, which are mostly constructed at the foot of cultivated hill slopes, are used for moisture conservation in the drought-stricken Tigray region of Ethiopia (Annen, 2006). They have also recently been used to grow fodder plants and perennials such as fruit crops. Alley cropping and hedgerows have been used for soil and water conservation in eastern and western Africa (Kiepe, 1995a; Spaan, 2003).

In general, development of traditional practices has been more effective than introduction of new practices (Reij, 2009). A range of indigenous soil and water conservation practices has evolved in SSA (Critchley et al., 1994). In Kenya, *fanya juu* (Swahili for ‘throw uphill’) terraces have been developed and widely used to conserve soil and water (Kiome and Stocking, 1995). They are constructed by digging a trench and throwing soil up-slope to form an embankment. The broad bed and furrow system and chat ridge systems were developed in the degraded eastern drylands of Ethiopia (FAO, 2009). In the drought-affected and degraded lands of northern Ethiopia, stone bunds are constructed along the contour, 30 cm wide and average height of 0.74m (Nyssen et al., 2007; WOCAT, 2010). They have been effectively used to reduce soil erosion, to shorten slope length and to retain soil moisture. In southern Ethiopia, the farmers of Konso are well known for their own traditional terraces, the best locally available technique for soil and water conservation. About 80% of the cultivated land is well terraced in Konso (EPA, 2004). Vegetation barriers, using local grasses, woody species and succulents, can reduce soil erosion by 70–90% in an alley-cropping system in central Burkina Faso (Spaan et al., 2005). Hedgerows of *Cassia siamea,* grown in a maize/cowpea rotation on 14% slopes in the Machakos district of Kenya, enable an average increase in infiltration of 30% in the dry season and 94% in the wet season (Kiepe, 1995b). Different modifications have been made to some of these practices to improve their performance. For example, farmers in Burkina Faso adapted the *zai* pits by increasing their depth and applying compost and manure. Application of compost and manure in the pits conserves water and supplies nutrients, hence enabling sorghum plants to establish better, grow faster and reach maturity before the rains cease. Hence, improvement of water availability and fertility in the crusted desert soils restored productivity to the area (Reij et al., 2009; Spaan, 2003).

2.2.2 Macro-catchment systems with water storage for supplementary irrigation

The macro-catchment rainwater harvesting systems usually consist of three components: the rainwater collection catchment, the storage structure, and the target area (Figure 2.2). In macro-catchment systems, the runoff is usually collected from external catchments and diverted into well designed storage structures. Although most of the macro-catchment rainwater harvesting techniques have a catchment area of less than 2 ha, in some cases runoff is being collected from catchments as large as 50 km2 (Makurira et al., 2007). The water is used either for supplemental irrigation during dry-spell occurrences or for domestic consumption. The ratio of the collection catchment to the cultivated target area can vary between 10:1 – 1000:1 (Liniger et al., 2011). Rainwater is collected from existing paved surfaces and natural slopes, and rarely from purpose-built structures. Runoff collection from upslope rock outcrops was found to be effective in Botswana (Carter and Miller, 1991). The system components and the storage volume, catchment type and area, and water applications, depend on the local rainfall pattern and soil types (WOCAT, 2010).

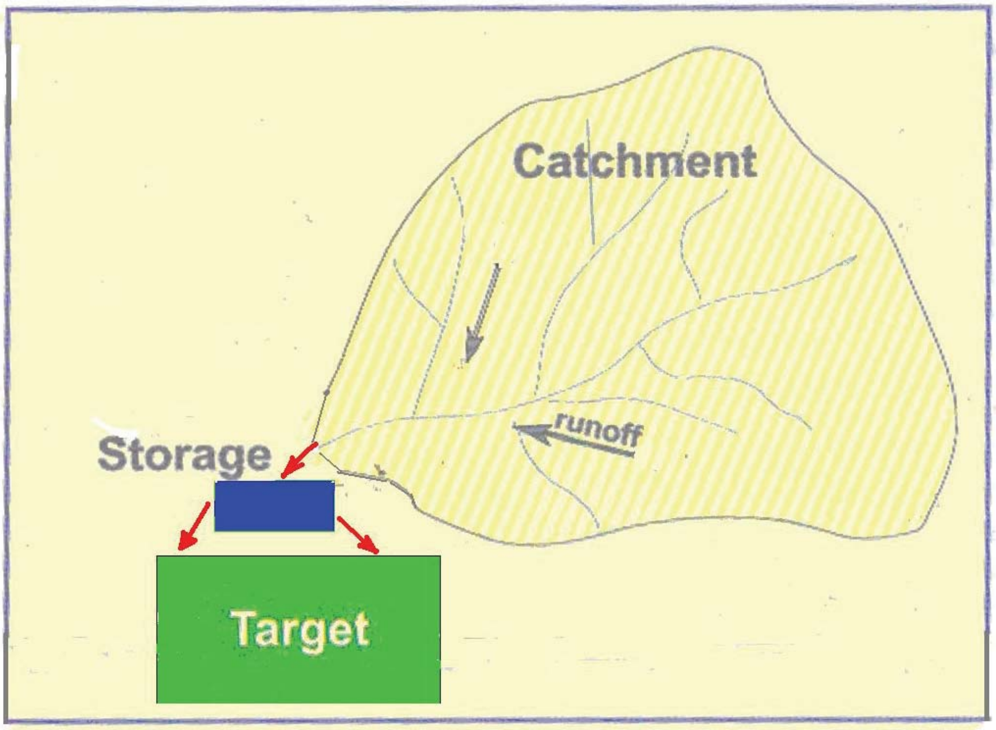

Figure 2.2. A typical example of a macro-catchment rainwater harvesting system (modified from Oweis et al., *2001).*

The most commonly applied macro-catchment rainwater harvesting techniques in SSA encompass traditional open ponds, cisterns, micro-dams, sand dams and spate-irrigation systems (Table 2.2). Several of the widely applied macro-catchment rainwater harvesting techniques are indigenous or modified from indigenous practices. The *birkas* (runoff-fed underground tanks) in the eastern Somali region of Ethiopia, *ellas* (deep wells) in the southern Borena area of Ethiopia and *hafir* (low earth dams) in eastern Ethiopia, have been traditionally used for livestock and domestic water supply (Habtamu, 1999). In the Hiraan region of Somalia, the *caag* system is used where considerable overland flow, or flow from a small *toog* (gully), is captured behind bunds (Reij, 1996). However, the commonly used traditional open rainwater ponds do have a short lifespan after the rainy seasons, as the water is lost *via* seepage (except for rock catchment dams) and evaporation. Seepage is a major problem in water storage in earthen reservoirs, accounting for losses up to 69% of the harvested water (Fox and Rockström, 2003).

Unlike the traditional open ponds, the recently developed cisterns in different parts of SSA are covered to reduce evaporation losses, and their walls are plastered to avoid seepage losses. The most important materials for construction and covering of these types of rainwater storage tank include cement, clay, clay-cement, lime-clay or lime-cement and polythene sheets. The cost of these materials makes macro-catchment rainwater harvesting systems expensive and poor farmers are discouraged from investing in them (Ngigi et al., 2005). However, in Ethiopia, locally available materials, such as termite-mound earth (either in blocks or as mud) are used to construct cisterns (Mills, 2004). Inspired by successful Chinese experiences, the Ethiopian government has given much attention to developing and promoting different designs of underground rainwater storage tanks —cisterns — in moisture-stressed, rainfed agro-ecosystems. Hence, in the four main administrative regions of Amhara, Oromia, Southern Region and Tigray, more than 340,000 cisterns were constructed in the years 2003–2004, mainly through government initiatives (Bekele et al., 2006).

Within the Kitui district of Kenya, about 500 sand dams have been developed over 10 years to store water for the dry season (Aerts et al., 2007). These sand dams are used for domestic water supply and irrigation, also enhancing groundwater recharge (Hut et al., 2008). The percentage of storage by sand dams relative to total seasonal runoff amounts to 3.8% for the April–October season and 1.8% for the November–March season (Aerts et al., 2007). In Tanzania, dugout ponds, which are found on roadsides where contractors have excavated soil for road construction, collect water, and villagers exploit this for domestic, livestock and vegetable production (Hatibu and Mahoo, 1999). In South Africa, *jojo* tanks of 0.75–20 m^3 have been popularised for collecting rainwater from rooftops, when it is used mainly for domestic purposes (Mokgope and Butterworth, 2001). Similar tanks of various designs have been promoted by non-governmental organisations in many African countries (Gould and Nissen-Petersen, 1999).

Spate irrigation is an indigenous technique of diverting and spreading seasonal heavy floods of short duration (Tesfai and Stroosnijder, 2001). It is commonly applied in SSA, in particular in Eritrea, Ethiopia, Kenya, Senegal, Somalia and Sudan. Farmers in Eritrea have used spate irrigation systems for more than 100 years, although modifications have recently been made through improved engineering skills (Tesfai and Stroosnijder, 2001). Similarly, a floodwater farming system known as *korbe* is practised in Ethiopia, which involves the diversion of water from various sources to grow vegetables, fruit trees and high-value crops on prepared land (WOCAT, 2010).

In addition to the simple diversion of storm flows from gullies and ephemeral streams into crop or pasture land, rainwater harvesting irrigation (RWI) from macro-catchment systems have eventually achieved recognition, as an alternative to conventional irrigation schemes (Rosegrant, 1997). There is a potential for reaching more than 30 million rural poor by applying supplemental irrigation to 15.2 million ha in SSA (Chartres, 2009). Supplemental irrigation, with about 100 mm of water provided during crucial dry spells, can double rainfed cereal yields from about 1 to 2 Mg ha^{-1}, increasing water productivity to 0.5 kg m^{-3} of water consumed (Araya and Stroosnijder, 2011; Rijsberman and Manning, 2006). Accordingly, the 50 m^3 rainwater tank commonly found in many parts of SSA could be used to apply supplemental irrigation for a farm plot of more than 500 m^2.

Table 2.2. Macro-catchment rainwater harvesting - Overview of the most commonly practised systems in Sub-Saharan Africa.

Type of macro-catchment systems	Description	Storage capacity (m^3)	Countries of wider application	References
Traditional open ponds	Runoff collected from cultivated hill slopes, natural watercourses, footpaths or cattle tracks is stored in un-plastered and open ponds. The stored water usually suffers from losses due to seepage and evaporation.	30-50	Mainly in East Africa (Kenya, Ethiopia, Tanzania, Somalia)	Habtamu (1999); Ngigi (2003); Reij et al. (1996)
Cisterns	Runoff collected from bare lands, cultivated hill slopes or road catchments is guided and stored in underground storage tanks. The cisterns have plastered walls and covered surfaces. In most cases, settling basins are attached in front of the inlet to reduce sedimentation and otherwise, regular cleaning is required.	30-200	East Africa (Kenya, Ethiopia, Tanzania, Uganda) South Africa (Zimbabwe, Botswana)	Wondimkun and Tefera (2006)
Earthen dams (Micro-dams)	Larger sized rainwater storage systems such as *ndivas* in Tanzania and micro-dams in Ethiopia are communally constructed around foots of hill slopes to store the runoff from ephemeral or perennial rivers. The reservoirs are neither plastered at their walls nor covered on their surfaces. The water is mostly used for supplemental irrigation communally and for cattle.	$(0.02\text{-}0.2)10^4$ in Tanzania, and $(0.1\text{-}3.1\ )10^6$ in Ethiopia	East Africa (Tanzania, Ethiopia) Southern Africa (Botswana) West Africa (Burkina Faso)	Haregeweyn et al. (2006): Makurira et al. (2007)
Sand dams	Dams constructed to store part of the natural flow in seasonal rivers. The sand carried by the river will settle upstream of the dam and gradually fill the streambed. Hence, the sand will reduce evaporation and contamination of the water in the sand body behind the dam.	-	East Africa (Kenya, Ethiopia)	Aerts et al. (2007); Hut et al. (2008);
Ephemeral stream diversions and spate irrigation	Ephemeral streams from uplands are diverted from their beds (*Wadis*) at the *agim* (temporary diversion structure) to irrigate adjacent crop fields downstream usually before planting.	-	Mainly in East Africa (Eriteria, Ethiopia, Tanzania)	Hatibu and Mahoo (1999); Tesfai and Stroosnijder (2001); WOCAT (2010)

2.2.3 Techniques for maximising infiltration, reducing surface runoff and evaporation, and improving soil water availability

Techniques for enhancing infiltration, reducing runoff and evaporation or for improving soil moisture storage in the crop rooting zone, are known as *in-situ* rainwater harvesting (Ngigi, 2003). These techniques generally do not need a runoff-inducing catchment area; rather, they are aimed at enhancing rainfall infiltration and reducing soil evaporation. The central idea behind these techniques is to turn blue water into green water to reduce direct soil evaporation, thereby causing it to be transpired through the plants (Falkenmark and Rockström, 2004). Better utilisation of rainfall to capitalise on green water requires appropriate land and crop management systems. Two distinct management periods are involved in maximising the use of precipitation for dryland crop production: the first period of rain storage, lasting from harvesting of the previous crop until planting of the next crop; and the second period, lasting from planting until harvesting of the crop (Bennie and Hensley, 2001).

The most commonly applied *in-situ* rainwater harvesting and management practices in SSA include ridging, mulching, various types of furrowing and hoeing, and conservation tillage (Table 2.3). Ridging - also known as furrow dikes, furrow damming, basin listing, basin tillage and micro-basins in different areas (Jones and Stewart, 1990) - can be designed as open or closed (tied) for holding water and facilitating infiltration in areas of low, erratic rainfall. In tied-ridging, sometimes also called ‘tied-furrows’, ridge furrows are blocked with earth ties spaced at fixed distances to form a series of micro-catchment basins in the field (Nyamudeza and Jones, 1994; Wiyo et al., 1999). Surface mulching, using both crop residue and material such as stones from non-cultivated areas, has long been used in SSA (Tengberg et al., 1998; WOCAT, 2010). Stone mulching has been promoted in Burkina Faso to check soil erosion and conserve moisture (Zougmoré et al., 2000). Conservation tillage (CT) in SSA encompasses a wide range of tillage techniques that have been tested and developed in many different places (Biamah et al., 1993; Fowler and Rockström, 2001; Temesgen, 2007). It covers a spectrum of non-inversion practices, from zero-tillage to reduced tillage, aiming at maximising infiltration and soil productivity, and minimising water losses while simultaneously conserving energy and labour. Recently, researchers have paid increasing attention to the development of appropriate conservation tillage practices suitable for dryland farming systems in SSA (ATNESA, 2010; Rockström et al., 2009).

Farmers in the northern drylands of Ethiopia make contour furrows at 2–4 m intervals - locally called *terwah* - for tef (*Eragrostis tef*) production (Gebreegziabher et al., 2009). These furrows trap water in the ridges in such a way that, after a storm, the fields will have elongated pools of retained water for later use by crops, instead of losing it as runoff. The traditional ridging and weed control practice known as *shilshalo*, is practised four weeks after planting of maize in Ethiopia (Birhane et al., 2006). In the central Rift Valley areas of Ethiopia, where sandy loam soils are sensitive to crusting, *shilshalo* is a means of breaking the surface crusts thereby enhancing infiltration (Biazin et al., 2011). The promotion of animal- and tractor-drawn conservation tillage among smallholder farmers in the semi-arid Babati district, Tanzania, using rippers and sub-soilers, has resulted in significant increases in water productivity in recent decades (Rockström et al., 2002). Similarly, in the semi-arid Laikipia district of Kenya small-scale conservation tillage, involving the use of ox-drawn rippers, was used to minimise soil disturbance and conserve soil moisture, while at the same time controlling costs and developing fodder (Liniger et al., 2011; WOCAT, 2007). In the semi-arid regions of the Sahel, where the soils are characterised by sealing, crusting, hard-setting and low organic-matter content, appropriate tillage techniques play a crucial part in improved infiltration and moisture conservation (Hoogmoed, 1999).

Table 2.3. ***In-situ*** **rainwater harvesting - Overview of the most commonly practised and emerging systems in Sub-Saharan Africa.**

Type of structure	Description	Regions of current application	References
Ridging	Basins that are wider than the traditional furrows are created either by manual hoeing or during tillage using a modified ploughing instrument. They can be designed to be tied every 3-6 m distance for holding water and facilitating infiltration in low and erratic rainfall areas.	Many parts of the SSA	Hulugalle (1990); Lal (1990); Wiyo *et al*. (1999)
Mulching	The use of both crop residues and material from non-cultivated areas, including stones, aimed at covering the soil. This improves infiltration of water into the soil and prevents evaporation out of the soil.	Western and Eastern Africa	Tengberg *et al*. (1998); WOCAT (2010)
Furrowing and pot-hoeing	Different furrowing techniques are used before and after planting to conserve soil moisture in areas where oxen ploughing and hand-hoeing practices are common. In the Sahel, small shallow holes are dug manually at correct intervals and the seeds are covered with soil; Two weeks after the emergence of the crop they add fertiliser about 10 cm from the plant.	Eastern and Western Africa	Birhane *et al*. (2006); Gebreegziabher *et al*. (2009); Nyssen *et al*. (2011)
Conservation tillage	It encompasses a wide range of tillage techniques ranging from non-inversion ploughing and reduced tillage to ripping and sub-soiling in SSA.	Many parts of SSA (South Africa, Kenya, Tanzania, Ethiopia,)	Rockström *et al*. (2002); Rockström *et al*. (2009); Temesgen (2007)

In Kenya farmers traditionally form trash lines from crop residues in surface strips along the contour, to mitigate erosion and exploit the trapped soil and moisture (Tengberg et al., 1998). This technique has also been promoted in the Kabale area of Uganda (WOCAT, 2007). In Uganda, dry vegetation is used to mulch bananas, pineapples and coffee in areas where soil moisture is a major constraint (WOCAT, 2010). Although appropriate application of crop residue mulch is essential to the rehabilitation of the desert soils in the Sahel (Mando and Stroosnijder, 1999), crop residues are often needed for income generation, or fed to livestock during the dry season, which limits the availability of mulch material in drylands (Sterk et al., 2001). Loglines, formed by logs unsuitable for charcoal production, are also used on recently cleared land as a soil and water conservation measure in Kenya (Okoba et al., 1998).

2.2.4 Techniques for improving plant water uptake and response farming

The experience of the past five decades has shown that genetic enhancements and appropriate agronomic management are important for increasing agricultural water productivity (Kassam et al., 2007). Genetic approaches to increasing the water productivity of crops encompass four traits (characters) of plants: (I) traits that reduce the non-transpiration uses of water in agriculture, (II) traits that reduce the transpiration of water without affecting productivity, (III) traits that increase production without increasing transpiration and (IV) traits that enhance tolerance of water stress (Bennet, 2003). As an example, early-maturing cultivars can escape droughts and provide yield even during years with below-average precipitation. A study conducted to determine the performance of late (120 days), early (90 days), and extra-early maturing (80 days) maize (*Zea mays* L.) cultivars, showed that extra-early maturing cultivars produced the highest dry matter yield, harvest index and grain yield in the Sudan Savannas of northeast Nigeria (Kamara et al., 2009). In another study, traits related to the ability of trees to extract and efficiently transport water, are suggested as the explanation for differences in drought resistance among species, and tree distribution in an arid savannah (Otieno et al., 2005).

Agronomic management for improved water productivity includes, but is not limited to, planting density and soil fertility management. Management of planting density according to the rainfall pattern has shown improved water and crop productivity in dryland rainfed systems (Tsubo and Walker, 2007). Too little plant density could lead to low utilisation of available soil water. The rapid establishment of a full ground cover due to a higher planting density can minimise the loss of water by evaporation from wet soil surfaces (Stewart and Steiner, 1990). The use of organic and inorganic fertilisers can also improve the water uptake capacity of crops. For example, farmyard manure improved the water-uptake capacity of grasses in the open grazing systems of Ethiopia (Tadesse et al., 2003). Managing optimum density that accord with a given crop requirements, different patterns of precipitation, and soil fertility can be valuable for improved water productivity.

Response farming is the system of predicting the seasonal rainfall at the start of each rainy season, and modifying the cropping systems accordingly (Stewart, 1988). The five key factors, which characterise a rainfall season for crop production, are: the onset and final rain dates, rainfall amount and distribution, duration, and intensity. The date of onset is of particular interest for two reasons (Stewart, 1988): (I) it occurs at the start of the season, before on-farm decisions are made, (II) it is highly variable and often a predictor of other rainfall attributes which occur later. On the basis of an analysis of long-term rainfall data, and knowing the crop response to different planting dates, it is possible to optimise the yield and water productivity of a given cropping system (Stewart, 1991). Analysis of long-term rainfall in the southern Sahelian and Sudanian zones revealed that delayed onset results in a considerably shorter growing season (Sivakumar, 1988). Hence, if the onset of the rains is delayed by 10 days beyond the calculated mean date of onset, short-duration cultivars or even alternative crops that will mature early, have a greater chance of being more productive (Sivakumar, 1988). Delaying the planting of maize generally increased days to flowering hence reduced dry-matter production and yield components (Kamara et al., 2009). Another study in Zimbabwe and South Africa showed that the late onset of rainfall during the maize growing season is associated with heavier rainfall, which could have negative consequences for crop yield if it leads to waterlogging (Tadross and Hewitson, 2005).

Apart from the onset, the distribution of rainfall throughout the growing season vitally affects crop productivity. For instance, agricultural dry-spell analyses from long-term rainfall data in two semi-arid regions of eastern Africa revealed that maize was exposed to at least one dry-spell of 10 days or longer in 70–84% of growing seasons (Barron et al., 2003). For many smallholder farmers in the semi-arid tropics, the risk of crop failure remains a reality every fifth year, with a risk of yield reductions every second year (Rockström et al., 2002). Farmers in semi-arid West Africa have tried to cope with low and erratic rainfall by, amongst other measures, decreasing planting density, replanting with early-maturing varieties or changing the crop type, and delaying fertiliser use (Matlon and Kristjanson, 1988). Recent advances in understanding and modeling of the oceanic atmospheric system at global and regional scales are important developments, which have enabled seasonal weather forecasting to assist farmers in optimising their immediate decisions and tactical planning with regard to the approaching season (Cooper et al., 2008). Response farming could be another potential research and development area for the future of green water capitalisation in SSA.

2.3 Research results on the performances of RWHM in SSA

2.3.1 Biophysical performances

Promising crop and water productivity performance has been observed from field evaluations of micro-catchment RWHM techniques in SSA. In the eastern drylands of Ethiopia, a field experiment was conducted to study the growth of four multipurpose tree species intercropped with grass (*Panicum maximum)* grown in plots with 25 m^2 and 100 m^2 micro-catchments (Abdulkedir and Schultz, 2005). The overall mean moisture content in the plots with micro-catchments was 31% higher in the wet season and 24% higher during the dry season, compared to that for plots without micro-catchments. The dry-matter content showed strong dependence on the area of the micro-catchments; the grass dry-matter yield was 32% greater on 100 m^2 plots, than on 25 m^2 plots. In Burkina Faso after the development of the *zai* pits, the farmers could rehabilitate their land and expand the size of their farms where nothing grew before (Kabore and Reij, 2004). Thus, crop yield was 0 Mg ha^{-1} without them, 0.3–0.4 Mg ha^{-1} in a year of low rainfall, and up to 1.5 Mg ha^{-1} in a year of good rainfall. Similar studies on *ngoro* pits in Tanzania revealed that 2-m wide pits had the highest maize grain yield (1.85 Mg ha^{-1}) compared to 1-m wide (1.44 Mg ha^{-1}) and 1.5 m wide pits (1.66 Mg ha^{-1}) (Malley et al., 2004). A maximum level of soil moisture around the introduced trenches and bunds in semi-arid Tanzania confirmed their effectiveness in concentrating the little available rainfall into green water-flow paths (Makurira et al., 2009).

The use of macro-catchment systems for rainwater irrigation has shown positive crop and water productivity responses in semi-arid areas of SSA as well. A survey and modelling study in semi-arid Zimbabwe implied that RWI from macro-catchment systems increases water productivity, from 1.75 kg m^{-3} up to 2.3 kg m^{-3}, by mitigating intra-seasonal dry-spells (Kahinda et al., 2007). RWI from hand-dug earth dams, in combination with fertilisation, increased the rainwater use efficiency of maize from 2.1 kg m^{-3} (non-irrigated and without fertilisation) to 4.1 kg m^{-3} (supplemental irrigation and 30 kg N ha^{-1}) during seasons with poor rainfall (< 300 mm) in Kenya (Barron and Okwatch, 2005). However, further studies are needed to bring about system improvements and to optimise RWI techniques. An on-farm study of rainwater harvesting irrigation by means of hand-dug earth dams in Burkina Faso showed that seepage losses accounted for 75%, and evaporation for about 5%, of the harvested dam water (Fox and Rockström, 2003). Similar studies in semi-arid Kenya revealed that seepage accounted for an average of 57%, and evaporation for an average of 12%, of the dam water (Barron and Okwatch, 2005). The irrigation efficiency of micro dams (*ndivas*) in Tanzania was found to be very low; more than 80% of the water was lost during conveyance from the dams to individual fields (Makurrira et al., 2007). Simple drip-irrigation kits have been widely regarded as the most promising technique, and have been successfully implemented in vegetable gardens in several countries of SSA (Karlberg et al., 2007). An on-farm study in a semi-arid area of Zimbabwe revealed that water savings of more than 50% were achieved in low-cost drip systems, compared to the conventional surface irrigation system (Maisiri, 2005). With this increase in water-use efficiency, a vegetable yield of 8.5 Mg ha^{-1} was obtained for drip irrigation, compared to 7.8 Mg ha^{-1} for surface irrigation. The overall irrigation efficiency of the traditional spate irrigation schemes in Eritrea is only about 20%, because of the difficulty of controlling floods and the loss of water *via* percolation, seepage and evaporation (Tesfai and Stroosnijder, 2001).

The crop and water productivity performance of *in-situ* rainwater harvesting techniques has also been examined in a number of on-farm studies. A three-year experiment conducted in the drought-stricken areas of Wollo region, Ethiopia, revealed that tied-ridging, open-ridging and sub-soiling improved soil water content in the root zone by 24%, 15% and 3%, respectively, as compared to traditional tillage during the cropping season (McHugh et al., 2007). In the semi-arid region of northern Ethiopia, where a significant proportion of the rainfall is lost as runoff, tied-ridges reduced surface runoff by about 60%, improving the soil-water content in the rooting zone by at least 13% (Araya and Stroosnijder, 2010). Accordingly, the grain yield of barley (*Hordeum vulgare)* could be improved by at least 44%. The moisture-retention capacity of tied-ridges was significantly higher than that of conventional tillage under sandy soils in Zimbabwe (Motsi et al., 2004). Thus the yield of maize under tied-ridges was twice that under conventional tillage without ridges. The tied-furrow system maintained significantly larger amounts of water in the soil, compared with flat cultivation, throughout the sorghum (*Sorghum bicolor* (L.) *Moench*) growing season in Zimbabwe (Nyamudeza and Jones, 1994). Earlier experiments in the West African Savannah also showed that runoff ranged from 0–15% with tied-ridging, whereas with either open ridging or flat planting, 20–40% of seasonal rainfall was lost as runoff (Hulugalle, 1990).

An on-farm experiment by Hensley et al. (2000) and simulation of crop yields with model combinations by Walker et al. (2005) in a clay soil of semi-arid South Africa showed that rainwater harvesting with basin tillage and mulching increased maize yields by 30–50%, depending on the initial soil water conditions. A field experiment conducted to examine the effect of stone mulching in Burkina Faso revealed that sorghum straw and grain yield were doubled on plots with stone lines, compared to that on plots without stone lines (Zougmoré et al., 2000). The soil water content decreased with increasing distance from the stone lines. The use of improved tillage through adaptation of the existing traditional *maresha* ploughing practices in semi-arid Ethiopia increased the yield of tef *(Eragrostis tef*) by 13–19% as compared to traditional tillage (Temesgen, 2007). A study in South Africa also revealed that better maize yields were obtained from no-tillage farming as compared to conventional tillage (Kosgei et al., 2007). However, because the effect of no-tillage farming on improving soil water status and crop yields depends on climate and soil type, local tests are required before the method is more widely applied.

The combined application of rainwater harvesting and soil fertility improvements has shown promising performances. Some rainwater management techniques, such as the *teras* system in Sudan, contribute directly and significantly to soil fertility through the deposition of sediment and organic matter (Niemeijer, 1998). In other cases, it is the addition of compost, manure or processed fertilizer to a system where RWHM is being employed that provides the increased benefit. In a semi-arid area of Burkina Faso, where sorghum production without water conservation techniques is very difficult, combining compost or animal manure with half-moon structures allowed yields between 0.9–1.6 Mg ha^{-1} i.e. 20–39 times that obtained in the half-moon without any compost or manure (Zougmoré et al., 2003a). A combination of manure application with *zai* pits in Burkina Faso also resulted in a more than twofold grain yield, compared with that obtained without manure (Fatondij et al., 2006). More than 5000 households have adopted composting in association with planting pits in the Boulgou province of Burkina Faso (WOCAT, 2007). In another on-farm study carried out in Burkina Faso, supplemental irrigation increased sorghum harvests by only 56%, but in combination with added fertiliser, by 208% (Fox and Rockström, 2003). As shown by a three-year experiment in semi-arid Tanzania, tied-ridging in combination with inputs of mineral fertiliser could increase maize grain yield from 1 Mg ha^{-1} (under flat planting with no mineral fertilisers) to 6 Mg ha^{-1}, and hence, the rainfall productivity (grain yield per unit of annual rainfall) could be tripled in near-normal rainfall years (Jensen et al., 2003). In the mixed crop–livestock systems of SSA, Integrated Soil Fertility Management (ISFM), combining different methods of soil fertility amendment with soil and water conservation, is found to be suitable (Liniger et al., 2011). ISFM involves maximising the use of organic sources of fertiliser, minimising the loss of nutrients, and judicious use of inorganic fertiliser according to need and economic availability. Many of these studies indicated that fertiliser application could substantially improve crop yields only in the presence of ample soil moisture. This implies that RWI is essential for encouraging fertiliser use by farmers who may not otherwise be willing to apply it, owing to the risk of crop failure caused by dry spells and drought.

The effect of the various RWHM practices on water and crop productivity depends on the rainfall pattern (Stroosnijder, 2007 and 2009). In rainfed lowland rice fields of south-eastern Tanzania, soil bunds can give a minimum yield increase of 30% in normal years, whereas in wet years and when the soil hardly drains (drainage class 0–5 mm day^{-1}), the yield may even double (Raes et al., 2007). Hatibu et al. (2006) indicated that investments in rainwater harvesting for paddy rice production in Tanzania give more benefits during above-average seasons compared to below-average ones. During years with well-distributed rainfall in the Sahel, water-conservation measures without addition of nutrients had little influence on crop yields (Zougmoré et al., 2003b). Hence, in years with well-distributed rainfall, application of nutrients alone resulted in much higher grain yields than did water-conservation measures without nutrient inputs. Mugabe (2004) reported that the difference in soil water content between access tubes at different distances from the *zai* pits was higher during dry spells, when tubes situated closer to the pits showed better soil-water status. Despite the beneficial effect of tied-ridges in years of near-normal (500–600 mm) rainfall, in wet years (700–900mm) waterlogging effects were observed on maize in Tanzania (Jensen et al., 2003). Hence, larger applications of fertiliser were recommended for alleviating excessive wetness by increasing water loss *via* transpiration. It is also imperative to consider the time of ridging, to obtain the best performance of the crop from it. Birhane et al. (2006) confirmed that tied-ridging before or at planting in arid areas of Tigray, Ethiopia resulted in a better soil-water status and the best crop performance, compared with tied-ridging after planting, especially when planting was in the furrow. Accordingly, pre-planting rain storage efficiencies could be improved by 2–37% by increasing the fallow period. On the other hand, Temesgen (2007) revealed that in the semi-arid Rift Valley of Ethiopia, the longer the interval between tied-ridging and sowing, the less were the water-conservation efficiency and the maize yield, provided that there was minimum rainfall in the interval.

2.3.2 Economic costs and benefits of RWHM

A number of studies have been undertaken to investigate the economic costs and benefits of rainwater harvesting and management in SSA. A detailed socioeconomic assessment was undertaken, with 1517 households in the four main administrative regions of Ethiopia, to examine the impact of micro-catchment and macro-catchment agricultural water-management techniques (Awulachew et al., 2008). The agricultural income (from both crops and livestock) was significantly ($p < 0.0001$) higher for users than for non-users of the techniques. An economic performance evaluation of rainwater harvesting techniques at field scale in Tanzania also indicated that investment in RWH for maize, paddy rice and onion productions was profitable in the long term, as long as farmers could afford the initial investment (Senkondo et al., 2004). Fox et al. (2005) made a cost-benefit analysis of rainwater harvesting for supplemental irrigation under maize (*Zea mays* L. var. Katumani B) in Kenya, and for sorghum *(Sorghum bi-color,* IRAT 204*)* in Burkina Faso, by setting the labour cost equivalent to the income forgone (income generated during an equivalent time spent in alternative production). Thus in Burkina Faso, from an earthen dam of volume 300 m^3, a net profit of US$ 151–626 ha^{-1} yr^{-1} was obtained, compared to a loss of US$ 83 to a meagre profit of just US$ 15 ha^{-1} yr^{-1} for current farming practices, depending on the labour opportunity cost. The net profit in Kenya was US$ 109–477 ha^{-1} yr^{-1} as compared to US$ 40–130 ha^{-1} yr^{-1} for current farming practices (Fox et al., 2005). The use of farm ponds for supplemental irrigation of maize, based on the two rainy seasons in Kenya, also provided net seasonal revenue of US$ 150, which could increase the annual return by 150% (Ngigi et al., 2005). This would give net revenue of US$ 300 *per annum*, based on the two yields from the two rainy seasons, and hence would require a payback period of four seasons. Rainwater harvesting linked to road catchments for production of paddy rice in Tanzania gave a gross margin of return of more than US$ 12 per person-day invested (Hatibu et al., 2006). These benefits are very high, because without rainwater harvesting, it is not possible to produce paddy in the study area, and a rainfed sorghum crop realises a return on labour of only US$ 3.7 per person-day during above-average seasons. However, the same study implied that investment to improve the rainwater harvesting systems by including storage ponds is not beneficial, owing to a higher labour requirement. Moreover, farmers in Ethiopia who have adopted rainwater harvesting irrigation properly have improved their dietary status (Desta, 2004).

The economic costs and benefits of the various RWHM techniques are highly influenced by nutrient inputs. Owing to the high cost of labour, transport and material inputs for the installation of stone rows or grass strips in Burkina Faso, these measures were not cost-effective without the addition of nutrients, although they gave a sorghum yield increase of 12–58%, particularly under poor rainfall conditions (Zougmoré et al., 2004). In Burkina Faso, a field experiment was performed to assess the impact of organic and mineral sources of nutrients and combinations thereof in optimising crop production in tillage and no-tillage systems, and to assess the economic benefits of these options (Ouedraogo et al., 2007). Hence, organic or combined organic and mineral-derived nutrient applications were recommended, in combination with water-conservation techniques, for improved economic benefits under semi-arid conditions. A study in Tanzania implied that those farmers who adopted macro-catchment rainwater harvesting (*ndiva*) systems tended to have better land management techniques (nutrient management and soil conservation) than non-users (Enfors and Gordon, 2008). A similar study in Ethiopia also indicated that the users of agricultural water-management techniques used more farm inputs (fertiliser and better seeds) than non-users (Awulachew et al., 2008). Analysis of over 10 years of agro-hydrological and agro-economic studies in southern Africa implied that implementation of the Millennium Development food security goals can be achieved through the combined use of fertiliser, better seeds and agricultural water-management techniques (Love et al., 2006).

The types of crop grown substantially influence the economic benefits obtained from supplemental irrigation through rainwater harvesting as well. Short-term economic profitability of supplemental irrigation in SSA could be made possible by shifting the current cereal-based farming into high-value cropping systems (Chartres, 2009). For instance, the net income of supplemental irrigation was 76% higher for onion than for green maize, through supplemental irrigation in the semi-arid Ethiopian Rift Valley (Bekele et al., 2006). The crops cultivated through rainwater harvesting irrigation in the predominantly cereal-based northern regions of Ethiopia were mainly root crops and vegetables (Wondimkun and Tefera, 2006). Using macro-catchment rainwater harvesting systems, many farmers in semi-arid areas of Tanzania have changed from the cultivation of sorghum and millet to paddy rice on the seasonally flooded black-cotton soils (Hatibu et al., 2006). In Uganda, contour bunds in pasture fields increased the availability of fodder, hence the farmers could decide when and at what price to sell their livestock, rather than being forced to sell them at throwaway prices to avoid death due to frequent droughts (Ngigi, 2003).

For investments in rainwater harvesting to have an impact on poverty reduction, increased linkage to profitable markets is critical, as the results show that increased cash income is a leading priority of farmers (Hatibu et al., 2006). When a market is not available for vegetables produced through rainwater-harvesting investments, storage and transportation could be a risk. Investments in agricultural water, and other priorities, can contribute to poverty reduction and provide returns through several pathways, including: higher productivity; higher employment; higher income and consumption; better nutrition and health; better education; lower variability in output, income, and employment; improved equity; multiple uses of water; and multiplier effects on non-farm sectors (Hanjira et al., 2009).

Despite the promising socioeconomic potential of RWHM, meagre success has been achieved in the wider dissemination of externally introduced techniques in SSA. Complexity, establishment costs and lack of fit with local practices are some key reasons. In many countries, the types of technique and the way they are implemented vary, due more to the preference of the donors and projects than to any physical, socioeconomic and agronomic differences (Spaan, 2003). For instance, the introduced soil and water conservation technologies in the western highlands of Ethiopia were characterised by a majority of the sample farmers as highly labour-intensive, with difficult designs to construct, conflicting with the free-roaming livestock grazing system and inapt for the existing land-tenure system (Bewket, 2007). A study on the role of socioeconomic factors on the performance and effectiveness of dead-level contours in semi-arid Zimbabwe revealed that resource ownership was a key factor in affecting their performance and farmers' ability to scale out the techniques (Munamati and Nyagumbo, 2010). In Ethiopia, although properly designed and implemented cisterns showed promising performances, they could not easily be adopted by smallholder farmers, mainly due to their unaffordable establishment cost (Shiferaw, 2006).

2.4 Discussion and conclusion

Owing to physical and economic water scarcity, subsistence rainfed agriculture will continue to be the predominant source of food for the rapidly increasing population in SSA. The grave agricultural water scarcity in this region is more associated with the variability of rainfall and the large non-productive water flows, than with the total annual precipitation. In drought-prone SSA, less than 15% of terrestrial precipitation takes the form of productive green transpiration. Hence, rainwater harvesting and management techniques have a significant potential for improving and sustaining the rainfed agriculture in the region. A wide variety of micro-catchment, macro-catchment and *in-situ* RWHM techniques is available in SSA. The indigenous techniques, or those modified from the indigenous RWHM practices, are more common and widely accepted by smallholder farmers than the introduced ones. A number of on-farm research results confirmed that micro-catchment and *in-situ* RWHM techniques could improve the soil water content in the rooting zone by up to 30%, hence substantially reducing non-productive losses. However, in heavy rainfall seasons, some of the techniques, such as tied-ridging and stone lines, could cause waterlogging on maize and sorghum. Strategies to address this are needed. Although initial investments on macro-catchment rainwater harvesting systems may be beyond the capacity of the poor, long-term economic analyses confirmed the substantial net profits achievable, compared to meagre profits or even losses from existing smallholder-based farming systems. As long as dry spells during the growing season are a vital cause of crop failure or severe productivity decline in drylands, more has to be done to further promote adoption of RWHM techniques. This is especially needed in the case of supplemental irrigation through macro-catchment rainwater harvesting systems.

Genetic enhancements, response farming and appropriate agronomic management techniques are also vital to increasing agricultural water productivity. Based on the study of long-term rainfall characteristics and seasonal weather forecasts, it could be important to provide early-warning systems and to plan appropriate crop-management tactics in response to the rainfall pattern during the approaching season. Integration of rainwater harvesting with soil amendments has shown spectacular performances. Depending on the rainfall pattern and types of crop, twofold to sixfold increase in crop yields - sometimes far more - may be possible from combinations of RWHM and nutrient inputs, as compared to the traditional practices. Without rainwater management, for many small-holder farmers in the semi-arid tropics, it is simply not worth investing in fertilization (and other external inputs) as long as the risk for crop failure remains a reality every fifth year with risk of yield reductions every second year, due to periodic water scarcity during the growing season (Rockström et al., 2002). In semi-arid western Africa, the use of N fertilizer alone was risky and a higher yield, with the accompanying economic benefit, was scarcely achieved under the prevailing rainfall conditions (Ouedraogo et al., 20007). The use of organic amendments, however, even without rainwater harvesting practices can contribute to increased water productivity and is affordable by the smallholder farmers. Continued research and development effort towards integrated RWHM, crop selection, and fertility management practices is needed in SSA.

Appropriate development of RWHM techniques is also irreplaceably vital as a practical and sustainable solution to the challenges of climate change and environmental degradation in this fragile region. Given the negative implications of climate change for the production of major agricultural crops in SSA (Schlenker and Lobell, 2010), rainwater harvesting will continue to be a viable adaptive strategy for people living with high rainfall variability, for countering droughts and mitigating flooding (UNEP, 2009). The Fourth Assessment Report of the International Panel for Climate Change (IPCC) has indicated that the expanded use of rainwater harvesting and other ‘bottom-up’ technologies, has the potential to reduce emissions by about 6 Gigatonne CO_2 equivalent yr^{-1} by 2030 (IPCC, 2007). Investigation of catchment hydrology in response to agricultural water use innovations indicated that rainwater harvesting through conservation tillage practices has influenced the partitioning of rainfall, by significantly reducing surface runoff over agricultural lands by up to 100%, as compared to conventional tillage (Kongo and Jewit, 2006).

Three decades ago, rainwater harvesting and management technologies had limited attention by research and development actors (Tabor, 1995). Recently, there have been research and development efforts by a number of regional or international organizations working in SSA (Humphreys and Bayot, 2009; Lininger et al., 2011; Rockström et al., 2004; Twomlow et al., 2008). The efforts to incorporate remote sensing and modelling techniques for the assessment of agricultural water management techniques and catchment hydrological responses has shown encouraging achievements in the region (Bastiaanssen et al., 1998; Jewitt, 2006; Kongo and Jewit, 2006; Kongo et al., 2010; Winnaar et al., 2007). However, the socioeconomic limitations to the development of appropriate RWHM technologies are still to be addressed. Farmers in SSA need technical and institutional support for developing their indigenous practices. The exemplary achievements of supplemental irrigation through rainwater harvesting for improved agriculture in the arid regions of China could be replicated in SSA, not only through appropriate support by local research and development, but also appropriate policy directives.

Facilitation of farmer-driven experimentation will allow farmers to methodically assess the value of the innovations they choose to study, while providing researchers with a venue for learning about socioeconomic as well as biophysical influences on farmers’ decisions (Sturdy et al., 2008; WOCAT, 2007). There is a need to identify integrated rainwater harvesting systems and to utilise indigenous knowledge as a decision-support tool for appropriate development (Mbilinyi et al., 2005). A methodology flowchart has been proposed as a decision-support tool to systematically out-scale the impacts of the micro-catchment and macro-catchment rainwater harvesting techniques to a catchment scale (Ncube et al., 2008). Based on a review of the various indigenous soil and water conservation systems in SSA, Critchley et al. (1994)

recommended that development projects need to incorporate indigenous practices in resource-conservation programmes. In northern Ethiopia, stone bunds could be popularised only after integrating them with the traditional knowledge of lynchets, locally called '*daget'* (Nyssen et al., 2000). Hence, more integrated efforts are needed to develop the indigenous practices, and to modify the introduced RWHM techniques in accordance with existing socioeconomic and biophysical settings. The much needed green revolution and adaptations to climate change in SSA should blend rainwater harvesting ideals with agronomic principles.

Chapter 3

Drought vulnerability and land-use changes in the Rift Valley drylands of Ethiopia

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Drought vulnerability and land-use changes in the Central Rift Valley drylands of Ethiopia

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Abstract

The Ethiopian Rift Valley is a dryland zone where for a long time pastoral communities have made their living from acacia-covered rangelands. But many farmers have changed from a pastoral way of life to mixed farming over time. The aim of this study was to evaluate land-use/cover dynamics in the Central Rift Valley drylands of Ethiopia, and determine the role of drought vulnerability as a driver. A combination of GIS/remote sensing techniques, drought vulnerability analyses, field observation and surveying were employed. The pastoral way of life was vulnerable to severe drought during 25% of the last 28 years, while the mixed farming system was vulnerable to severe drought only during 4% of the years. Over the last 5 decades, cultivated lands increased to threefold while the dense acacia coverage declined from 42% in 1965 to 9% in 2010. The observed land-use changes were driven by the interplay of recurrent drought, socioeconomic changes, institutional dynamics, access to markets and improved technologies such as early-maturing maize cultivars and better land management. The same trend of land-use/cover change tends to happen in the rest of the Rift Valley drylands where a pastoral way of life is still present.

3.1 Introduction

Drylands cover about 41% of Earth's land surface and are inhabited by about one third of world population (more than 2 billion people) (FAO, 1998; White et al., 2002). According to the UNCCD (2000), drylands are characterized by a ratio of annual precipitation to potential evapo-transpiration (P/PET) ranging between 0.05 and 0.65. The FAO (2000) has also defined drylands as those areas with a growing season length of 1-179 days and a climatic classification of arid, semi-arid and dry sub-humid. The UNEP (1992) definition of drylands encompasses the hyper-arid areas with the P/PET ratio of less than 0.05 as well. By 2020, about 3 billion people will reside in arid and semi-arid environments (Fisher and Helig, 1997). Although every continent contains lands with these zones, drylands are most extensive in Africa (nearly 13 million km^2) and Asia (18 million km^2) (UNDP, 1997). Over 40% of low-income countries are largely drylands, where local people mainly depend on agriculture for their living. In Ethiopia, the drylands occupy 65% (close to 700,000 km^2) of the total land mass of the country (EPA, 1998), and 46% of the total arable land (Yonas, 2001).

Dry lands are a vital part of the earth's human and physical environments. They encompass rangelands, arable lands, forests and urban areas (Koohafkan and Stewart, 2008). Rangelands (i.e. grasslands, shrub lands, savannas, tundra, etc.) previously occupied more than 51% of the earth's terrestrial land surface and supported more than 50% of the world livestock (Allen-Diaz, 1996). Land-use changes including deforestation, intensification of agriculture, and urbanization have been occurring rapidly at the expense of rangelands (Lambin et al., 2001; Reenberg, 2001). A unidirectional and yet rapid conversion of rangelands and woodlands to cultivated lands was reported in many parts of Sub-Saharan Africa (SSA) during the 1980s and 1990s (Garedew et al., 2009; Lambin et al., 2003). However, in the Sudano-Sahelian zones of Ghana and Burkina Faso, there was a bidirectional pattern of land-use changes from woodlands to parklands (0.44-0.77% year^{-1}) and vice versa (0.25-0.45% year^{-1}) due to regeneration of savannah woodlands on abandoned farmland and long-term fallows during 1986-2001 (Reenberg, 2001; Wardel et al., 2003). Despite the growing consensus about the increasing degradation of woodlands and grasslands in Sub-Saharan Africa (Diouf and Lambin, 2001; Mortimore and Turner, 2005; Reenberg and Lund, 1998), there are uncertainties about the real image of the changing trends and the drivers behind them (FAO, 2006; Grainger, 2010).

The Ethiopian Rift Valley, covering the huge proportion of the Ethiopian drylands, has long been occupied by pastoral communities making their living from rangelands (Abule et al., 2005). Having the largest livestock population in Africa, Ethiopia gets about 30% of its gross national product and 12-15% of its total export earnings from this sector (Solomon et al., 2003). The Ethiopian Rift Valley is also home to a chain of lakes that vary in size, and hydrological and hydro-geological settings (Ayenew, 2004). These lakes are used for irrigation, soda extraction, commercial fish farming, and recreation, and they support a wide variety of endemic birds and wild animals. Despite its huge environmental and economic benefits, the Ethiopian Rift Valley is faced with pressing natural and anthropogenic challenges. Drought, overgrazing and increases in human population are the perceived problems of the pastoral communities in the Ethiopian Rift Valley (Abule et al., 2005; Angassa and Oba, 2010). A study based on the long-term records of rainfall and cattle population data in the southern Rift Valley drylands of Ethiopia revealed that annual rainfall variability strongly influenced the dynamics of cattle population, calving rates and mortality (Angassa and Oba, 2007). Droughts in 1983-85 and 1991-93 resulted in the deaths of 37% and 42% of all cattle, respectively (Desta and Coppock, 2002). The declining condition of the livelihood of the pastoral people is evident on numerous levels such as changing trends in livestock holding and declining productivity (Solomon et al., 2007).

So far there have been only three studies on land-use and land-cover changes in the vast Rift Valley drylands of Ethiopia (Dessie and Kleman, 2007; Garedew et al., 2009; Tsegaye et al., 2010). All of these studies reported that there has been a steady rate of conversion from rangelands and native woodlands to cultivated arable lands during the last four decades. But these studies were all undertaken far from the main Central Rift Valley (CRV) where the remnant acacia-based woodlands are present. Garedew et al. (2009) reported that in the two villages of the Rift Valley, the woodland areas decreased by 85% in Keraru and 100% in Gubeta-Arjo while the cropland area roughly increased in similar rate by 126%.

Beyond quantifying the land-use and land-cover changes using GIS/remote sensing techniques, a thorough understanding of the interaction of the changes with the main bio-physical and socio-economic drivers is required for the development of informed and appropriate land use policies in the Rift Valley dry lands of Ethiopia. Based on the people's accounts, Tsegaye et al. (2010) reported that severe drought during 1973/74 and 1984/85 stimulated land-use changes from rangeland into cultivated arable land, with maize being the most widely cultivated crop in the Northern Rift Valley of Ethiopia. Thus, for a further scientific understanding of the effect of drought on land-use conversions, a comparison of the drought vulnerability of the pastoral way of life and the mixed farming system based on long-term rainfall records is needed. Having the sensitivity of the pastoral people to drought-shocks (Carter et al., 2004), the loss of livestock or decline in productivity after drought might have initiated land-use conversion to smallholder mixed-farming system as a better coping strategy. In this study, we hypothesized that drought vulnerability of the pastoral way of life along with the burgeoning population has triggered land-use conversions in the CRV of Ethiopia.

The objective of this study was, therefore, to evaluate land-use/cover dynamics, and determine the role of drought vulnerability as a driver for land-use change amid socio-economic and institutional changes in the Central Rift Valley drylands of Ethiopia. Based on long-term rainfall data, the probability of drought either for livestock or maize cultivation was evaluated as a driver for land-use changes. In addition, the study tried to investigate the socio-economic factors, institutional changes, and access to improved technologies and markets that might affect the trends of land-use changes. The results of this study may be used as valuable information for initiatives in the sustainable management of the drought-prone and fragile Rift Valley drylands.

3.2 Material and methods

3.2.1 Description of the study area

The study was conducted in the CRV of Ethiopia around Langano (Figure 1.1) which is situated approximately 200 km south of the capital, Addis Ababa. It covers an area of 63 km^2 of which 46 km^2 is owned by the local farmers, 16 km^2 is communal land (mainly around the shore of nearby lake Abijata), and 1 km^2 is occupied by the Abijata-Shalla National Park. The study area is bordered by Lake Abijata in the west and Lake Langano in the East. It lies between 1580 m (at the borders with the lakes) and 1660 m above sea level. The area is covered with volcanic and sedimentary rocks (Ayenew, 2007). The soil is shallow and poor in fertility with a texture ranging between loamy sand and sandy loam (Biazin et al., 2011a; Itanna, 2005). It readily compacts and is liable to crusting and drought.

The area was previously covered by dense acacia woodlands consisting of four main acacia species (*Acacia tortilis*, *Acacia senegal, Acacia seyal* and *Acacia etbaica)*. The acacia woodlands were used by the pastoral Oromo people (Eshete, 1999), and there were no permanent cultivated lands before the 1950s. In recent decades, the woodlands have been steadily converted to a sedentary and subsistent mixed farming system, with the remaining acacia trees scattered in the grasslands and rarely present in patches. A key factor in this is likely the increase in the human population since the 1950's, from only a few persons per km^2 to about 93 persons per km^2, as interpolated from the population census of the Arsi Negele District (CSA, 2008). Major crops grown in the area are maize (*Zea mays* L.) and haricot bean (*Phaseolus vulgaris* L.). Livestock includes mainly goats and cattle. Most grazing is done by free roaming throughout the year. Following crop harvests, livestock can also freely graze on the crop residues.

The mean annual rainfall in the area from 1981 to 2010 was 655mm (CV= 30%) and the mean annual potential evapo-transpiration over the same period was 1740 mm. Recurrent droughts associated with low annual rainfall records have been observed during the last three decades. However, the majority (78%) of the rainfall records below the mean have been observed since 1990 (Figure 3.1). Seleshi and Zanke (2004) correlated the persistent decline in rainfall during 1986-2002 with the warming of the South Atlantic Ocean and the higher pressure over the tropical eastern Pacific Ocean. The monthly climatic characteristic of the study area is summarized in Figure 3.2.

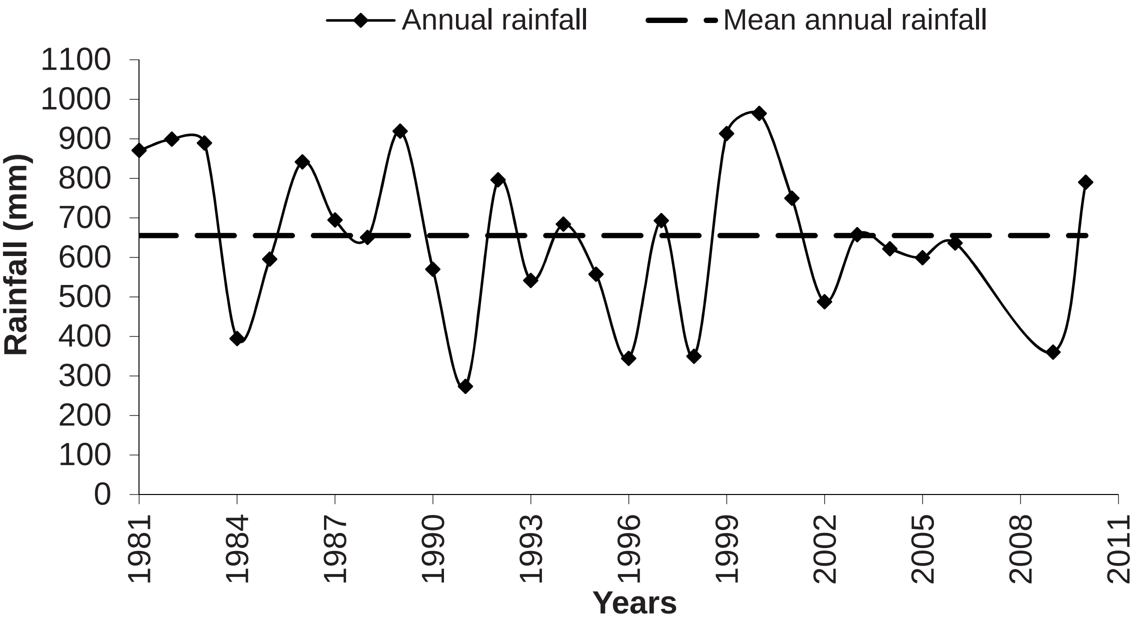

Figure 3.1. Annual rainfall during 1981-2010 in Langano, CRV of Ethiopia.

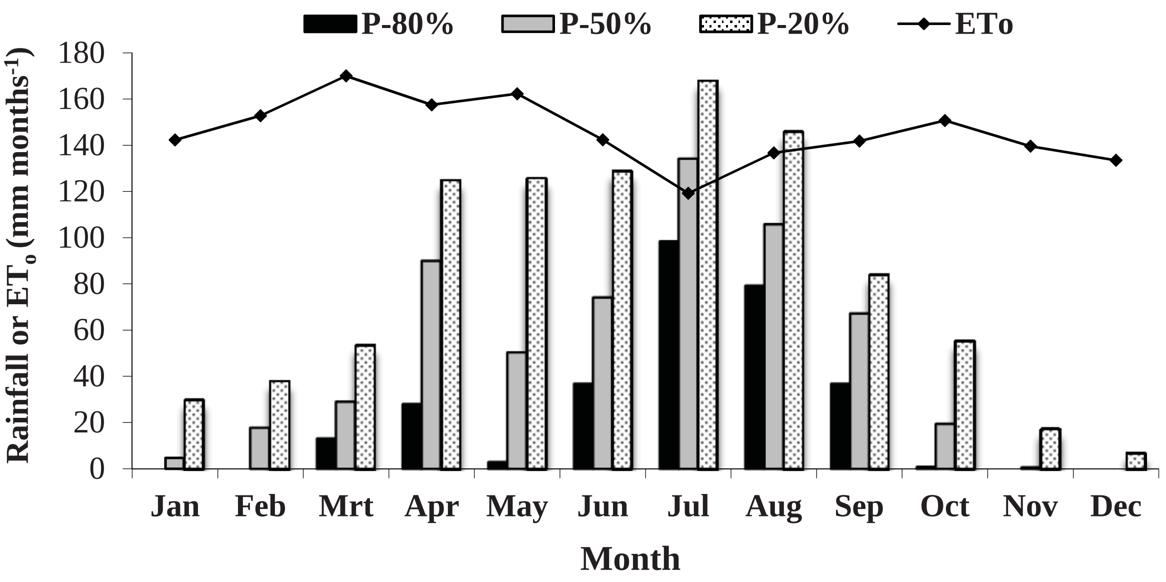

Figure 3.2. Mean monthly reference evapo-transpiration (ET_o) and monthly rainfall at 20% (P-20%), 50% (P-50%) and 80% (P-80%) probability of exceedance in Langano, CRV of Ethiopia.

3.2.2 Methods

Predictions of land-use changes and their drivers require multi-disciplinary analyses (Veldkamp and Lambin, 2001). A combination of three techniques was used to determine the dynamics in land-use and the drivers behind them. First, the extent and trend of land-use changes over the last five decades was analysed through GIS/remote sensing techniques and field observations. Secondly, based on meteorological analyses of long-term rainfall data, drought vulnerability of the two prevailing farming systems (pastoral way of life and crop-livestock mixed farming) was examined. Thirdly, two socio-economic surveys were undertaken to examine the socioeconomic characteristics, and the perceptions of the local people toward the land-use changes and the drivers behind. The hypothesized role of drought in triggering the identified land-use changes and related adaptations in land management was explained using the combined results of drought vulnerability analyses and the socioeconomic survey.

3.2.2.1 Land-use/cover data acquisition and analyses

The data sources included aerial photographs from 1965, two sets of satellite images taken in 1986 (Thematic Mapper, acquired in January) and 2000 (Enhanced Thematic Mapper, acquired in February), and ground measurements carried out during 2010 due to lack of quality satellite images for recent years. The aerial photographs were the only sources of information before the launch of satellite images, and were obtained from the Ethiopian Mapping Authority. The satellite images were browsed from the Global Land Cover Facility (Source: http://www.glcf.umd.edu/data/landsat). Land cover is the observed biophysical cover on the earth's surface, whereas land-use is characterized by the arrangements, activities and input people undertake in a certain land cover type to produce changes or maintain it (Di Gregorio, 2005). Based on the new land cover map of Africa (Mayaux et al., 2004) and some minor modifications according to the local situations, the land-uses/covers of the study area were categorized into five classes (Table 3.1).

The aerial photographs were scanned and geo-referenced according to the Universal Transverse Mercator (UTM) system using 1:50,000 topographic maps. Hence, classification of the different land-uses/covers on the aerial photographs was done based on stereoscopic and digital interpretations. A supervised maximum likelihood method was used to classify the land-use/covers on the satellite images. The satellite images were first corrected for error in ERDAS IMAGINE and then classified into 35 spectral classes in Multi-Spec (multispectral image data analysis software application, Biehel and Landgrebe, 2002).

Table 3.1. Descriptions of the land-use/cover types in Langano area, CRV of Ethiopia.

Land-use/cover	Description
Dense acacia woodland	Acacia-based woodlands where the acacia trees cover approximately more than 40% of the ground surface
Scattered acacia with grass undergrowth	Acacia trees with canopy coverage of approximately between 10 and 40%, grasses being abundantly present in the open spaces and under the acacia trees. It also encompasses settlements as the local people often retain acacia trees for shading around their courtyard.
Grassland	Grass being the dominant plants with the canopy of acacia trees covering approximately less than 10% of the ground surface.
Cultivated land	Areas used for crop cultivation mainly of rainfed maize and haricot bean with rarely other cereals such as barley (*Hordeum vulgare*) and teff (*Eragratis teff*).
Bare land	Surfaces not covered by any type of vegetation mainly including sands, rock outcrops, roads, cattle tracks, or exposed soils not used by any of the above land cover types.

They were reclassified into the five land-use/cover classes and the area coverage was determined in Arc GIS (version 9.2). During January-February 2009 and March 2010, an intensive ground truthing was undertaken by taking 131 GPS points systematically from anywhere in the study area. Hence, the types of land-uses/covers on the sampled points during 1965, 1986 and 2000 could be labelled by owners of the respective lands and elderly persons.

During February – April 2010, intensive ground measurements were applied to study the existing land-use/cover scenarios. Five parallel transects were aligned across the study area. From each homogenous land-use/covers crossed within the transects, quadrants (10m x 10m area) were sampled to examine the proportion of soil surface covered by the acacia trees. Surface observations were also made in each quadrant to identify bare lands, grasslands and cultivated lands. Hence, the length of the different homogenous land-use/cover types were measured with GPS within each of the transects. Finally, the ratio of the total length of each land-use/cover to the total length of the transect could be used to estimate the percent of the respective land-use/cover types.

3.2.2.2 Analysis of rainfall characteristics and drought vulnerability

The probability of drought (bad years, *Bona*, according to the farmers) was examined separately for livestock keeping and maize (the staple crop) farming based on locally perceived criteria. This was done to determine if the use of a maize-livestock mixed farming system can enable farmers to better cope with drought than the pastoral way of life. To examine the probability of drought, three criteria were set: onset, dry-spells of different lengths and cessation of the rainy season. The onset of the rains was previously defined for semi-arid areas either in Ethiopia (Simane and Struik, 1993; Tesfaye and Walker, 2004) or in other semi-arid areas of Africa (Barron et al., 2003; Sivakumar, 1988). Based on discussion with the local farmers, the onset of the rainy season–considered to be a successful planting date for maize in the CRV–was defined as the first occasion after March 1 when the rainfall accumulated in 5 consecutive days is at least 30 mm and when there was no dry spells (< 0.85 mm d^{-1}) of more than 15 days in the following 30 days. Dry spells of up to 20 days could be accepted when the 5 days cumulative rainfall during the onset is 60mm or more. Similarly, the onset of the rainy season from the perspective of livestock keeping was also defined as the first occasion after January 1 when the rainfall accumulated in 5 consecutive days is at least 20mm and no dry-spells (< 0.85 mm d^{-1}) of more than 30 days occurs in the following 60 days. This onset should enable the wooded grasslands to start sprouting for successful grazing by the livestock following the extended dry seasons in the CRV. The cessation of the rainy season for maize was defined as “the first day of a dry spell (< 0.85mm d^{-1}) of at least 20 days that occurred after onset” (Segele and Lamb, 2005). However, this definition of cessation was not applied when extended dry periods of more than 20 days occurred in mid-season, after which persistent rains returned.

A first-order Markov chain was fitted to get the probability of rainfall occurrences and different lengths of dry spells using the software INSTAT version 3.36 based on the method described by Stern et al. (2006). The Markov chain model has been applied many times for rainfall and drought analyses (e.g. Barron et al., 2003; Biamah et al., 2005; Gabriel and Neumann, 1962; Sharma, 1996; Stern and Coe, 1984). The Markov chain probability model assumes that the probability of rainfall on any day depends only on whether the previous day was wet or dry, i.e., whether rainfall did or did not occur. A dry day is defined as a day receiving less than 0.85 mm of rain (Barron et al., 2003; Stern et al., 2006). Hence, according to the first-order Markov chain, the probability of a day being wet is determined by the probability of the previous day being wet ($P\ (rr)$) or previous day being dry ($P(rd)$). In a given year (x_i), there are a sequence of wet ($x_{i,j} = 1$) and/or dry days ($x_{i,j} = 0$) (Equation 3.1).

$$x_{i,j} = \{x_{i,1}, x_{i,2}, \ldots, x_{i,365}\} \qquad \text{for each } i = \{1, 2, \ldots, n\} \text{ and } j = \{1, 2, \ldots, 365\} \qquad [3.1]$$

Where:
i refers to the year number counted from 1 to n during the data set, and
j is the day number in a given year.

The probability of a day being wet following a dry day ($P_j(rd)$) is estimated by Equation 3.2. Likewise, the probability of a day being wet following a wet day ($P_j\ (rr)$) is estimated by Equation 3.3.

$$P_j(rd) = \frac{\sum_{i=1}^{i=n}(x_{i,j} = 1, x_i, _{j-1} = 0)}{\sum_{i=1}^{i=1}(x_i, _{j-1} = 0)} \qquad [3.2]$$

$$P_j(rr) = \frac{\sum_{i=1}^{i=n}(x_{i,j} = 1, x_{i,j-1} = 1)}{\sum_{i=1}^{i=n}(x_{i,j-1} = 1)} \qquad [3.3]$$

Dry-spells of length m are defined as a sequence of m-dry days preceded and followed by dry days whereby the lengths of successive spells are readily seen to be independent. Based on experiences on agricultural dry spells in semi-arid tropical SSA (Barron et al., 2003; Fox and Rockstrom, 2000; Sivakumar, 1992; Tesfaye and Walker, 2004) and the farmers’ interviews, the probabilities of dry spell lengths of 7, 10, 15 and 20 days were determined for the growing season. INSTAT was used to fit the best function for the probability of rainfall occurrences. Subsequently, this fitted function was used to determine the probability of dry spells of the aforementioned lengths. Daily rainfall data was obtained from the Langano Meteorological site (during 1981- 2006) and an automatic weather station (during 2009 -2010).

Based on the farmers’ criteria, the characteristics of drought (*Bona*) years for maize cultivation or livestock keeping were defined (Table 3.2). Severe drought years for maize cultivation refer to those years when maize cultivation totally failed while moderate drought years are those years when maize productivity was severely limited due to one or more of the perceived criteria during the growing season (Table 3.2). Similarly, regarding livestock, severe drought years refer to years when death of livestock occurred due to the late onset of the rainfall while moderate drought years are those years when the livestock productivity was severely reduced. Based on the outcome of these analyses, the probability of drought either for the pastoral way of life or maize-livestock mixed farming system could be calculated.

Table 3.2. Description of drought years for maize cultivation and livestock keeping in Langano area, CRV of Ethiopia.

Perceived criteria	Severe drought for maize	Moderate drought for maize	Severe drought for livestock	Moderate drought for livestock
Onset of rainfall	When onset is after June 15	NA	When onset is after March 31	When onset is between February 28 and March 31
Dry-spells	Greater than 30 days of dry spells during the first 60 days after onset, or greater than 20 days of dry spells during 60-90 days after onset	Between 20 and 30 days of dry spells during the first 60 days after onset, or 10-20 days of dry spells during 60-90 days after onset	NA	Greater than 60 days of dry spells during the first 200 days after onset
Cessation of rainfall	When the cessation is in less than 90 days after onset	NA	NA	NA

'NA', when a criterion is not applicable

3.2.2.3 Socio-economic survey

Two socio-economic surveys were carried out with 66 farming households (8 women and 58 men) from March to September 2008. Summary of the characteristics of the respondents is presented in Table 3.3. In each of the two surveys, focused group discussions with selected stakeholders and semi-structured interviews with key informants preceded the formal questionnaire. The focused group discussions enabled formulation of thorough and well-thought out survey questionnaires. The first survey was undertaken to determine the socio-economic situation and collect relevant data on household characteristics, farm sizes, land tenure, crop and livestock farming systems, etc. The second survey focused on investigating the trend of change in land-use, past and current land management systems, and the perceptions of the smallholder farmers to agricultural problems.

The survey questions were designed to investigate the real drivers behind the perceived changes. The role of agroclimatic challenges, socio-economic factors, institutional dynamics, and access to improved farming technologies and markets was explored. The perception of the local people to the trend of agricultural drought and the coping strategies used by the different households were also examined. The relative importance of mixed farming over the pastoral way of life in coping with drought was, therefore, thoroughly discussed. Accordingly, the coherence between the meteorological analyses and the people's responses could be investigated. The most important agricultural technologies and better land management techniques that have been introduced and adopted by the local people were also examined. The three years of 1965, 1986 and 2000 represented three different regimes, namely that of the emperor Haille Selasie, the Socialist Derg and the current government, respectively. Therefore, the effect of institutional changes on the trend of land-use changes could also be explored based on the peoples accounts.

Table 3.3. Characteristics of the sample households in Langano area, CRV of Ethiopia.

Household characteristics	Mean	Standard deviation
Age (years)	46	12
Family size	8	2
Number of oxen	3	2
Number of goats	11	8
Landholding size per household (ha)	5.4	3.2
Number of farm plots	2	1

3.3 Results

3.3.1 Land-use dynamics during 1965-2010

The changes in the land-use/cover types and their statistical summaries are presented in Table 3.4. Figure 3.3 depicts the spatial distribution of the different land-use/cover types in the years 1965, 1986 and 2000. The dense acacia vegetation consistently decreased from 42% in 1965 to 9% in 2010. The total land area covered by both dense and scattered acacia decreased from 77% in 1965 to 40% in 2010. On the other hand, the area of cultivated land increased from 10% in 1965 to 29% in 2010. Accordingly, the annual conversion into cultivated lands was 33 ha year^{-1} between 1965 and 1986, 23 ha year^{-1} between 1986 and 2000 and 18 ha year^{-1} between 2000 and 2010 implying a decreasing rate of conversion with time. Although scattered acacia coverage was decreasing until 2000, it has again increased during the last decade mainly due to the conversion from the dense acacia. Although the grassland cover was increasing between 1965 and 2000, it has again slightly decreased between 2000 and 2010. The decrease in the proportion of bare land from 1965 to 1986 was mainly due to succession of grasses on sand accumulations around the shore of Lake Abijata. However, following the expansion of sand mining by the local people during the last 15 years, removal of the grasses again increased the area of bare land.

Around the beginning of the 1960's a few landlords used mechanized clearing of the woodlands extensively to convert to cultivated lands. The continuous and extended areas of cultivated land seen on the map developed from the aerial photographs of 1965 explain this fact (Figure 3.3). However, following the change in government in 1974, the 1975 land reform proclamation of "land for the tillers," enabled land ownership by individual households. Thereafter, small and fragmented plots of cultivated lands became evident. The majority of the land owners (89% of the respondents, N= 66) acquired their land from the government either during the Marxist Derg in 1975 or from the current government. Only the remaining 11% of the respondents (most of whom are young farmers) inherited their lands from their parents. The majority of the local people (98% of the respondents, N=66) are still increasing the size of their cultivated lands at the expense of grasslands and acacia woodlands but to a lesser extent compared to the previous decades. Soil fertility (71% of the respondents), moisture retention capacity of the land such as valley bottoms (26% of the respondents) and proximity to villages (3% of the respondents) were mentioned as the primary factors for a certain piece of land to be chosen for maize cultivation. On the other hand, steep slopes (47% of the respondents) and rock outcrops (26% of the respondents) were constraints against using a given land for crop cultivation.

Table 3.4. Temporal dynamics of the different land-use/cover types in Langano, the CRV of Ethiopia.

Land-use/cover type	Area in 1965		Area in 1986		Area in 2000		Area in 2010	
	ha	%	ha	%	ha	%	ha	%
Dense acacia	2645	42	1694	27	1031	16	563	9
Scattered acacia	2190	35	2024	32	1420	23	1939	31
Grassland	70	1	905	15	1485	24	1189	19
Cultivated land	622	10	1314	21	1631	26	1814	29
Bare land	729	12	319	5	689	11	751	12
Total	6256	100	6256	100	6256	100	6256	100

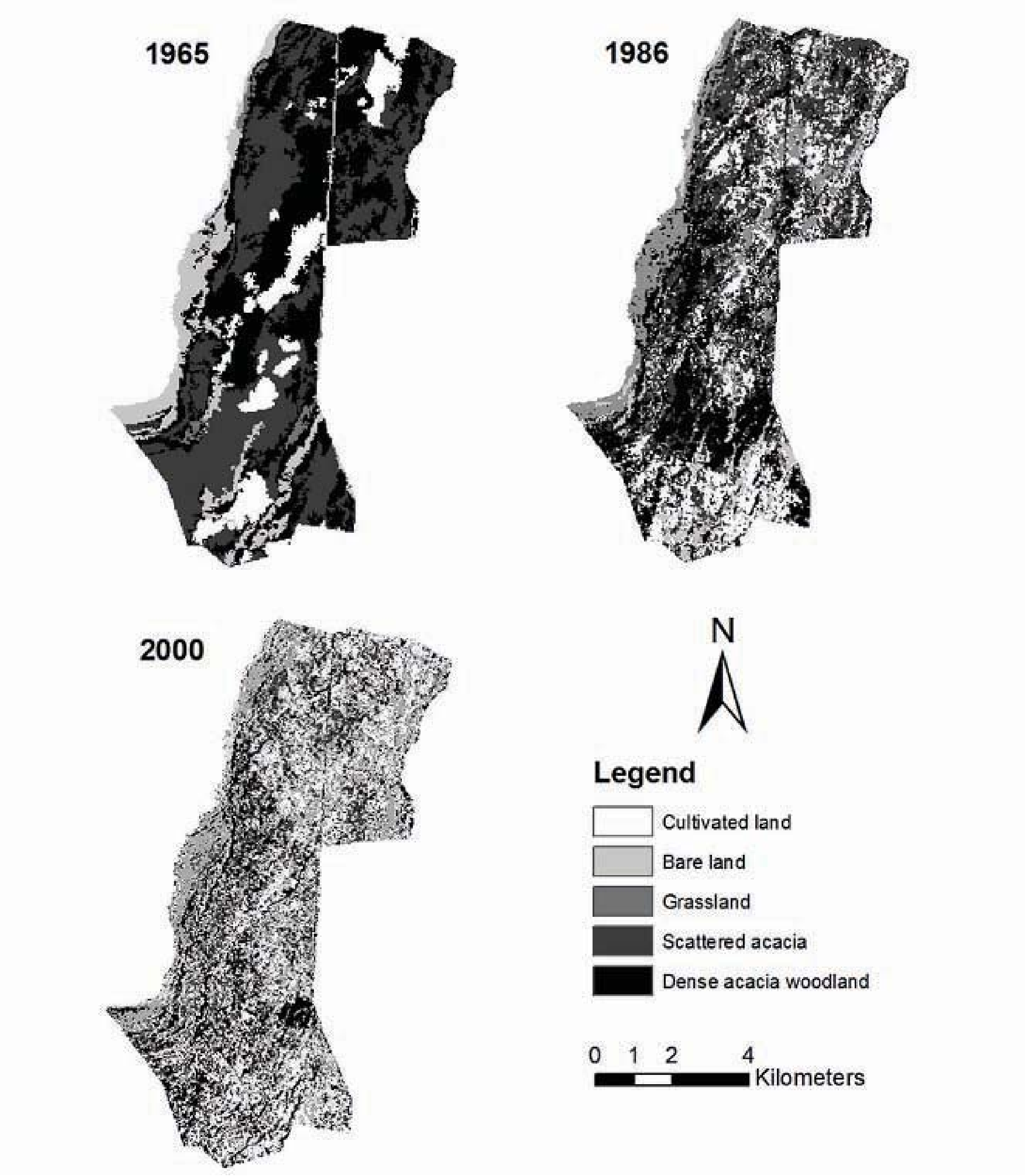

Figure 3.3. Land-use/cover maps for the years 1965, 1986 and 2000 in Langano area, CRV of Ethiopia.

3.3.2 Agro-climatic characteristics and drought vulnerability

The inter-annual variability of the onset of the rainfall is high for both maize farming (Mean = May 9; SD = 32 days) and livestock keeping (Mean = March 4; SD = 33 days) in the CRV (Figure 3.4). Following the extended dry season, the higher probability of rainfall occurrences *P*(*r*) in April and May (Figure 3.5) could explain why the local farmers usually sow their maize during this period. The highest probability of rainfall occurrence is attained between July and August which would be the best time for flowering and grain filling of maize (Figure 3.5). The higher probability of receiving rain given the previous day being rainy (*P* (*rr*)) compared to the probability of rain given previous day being dry (*P*(*rd*)) was in line with a previous study in Eastern African drylands (Barron et al., 2003). However, the high probability of dry spells during the maize growing season (Figure 3.6) could constrain the potential yield of maize in the smallholder based rainfed system. The lowest probability of occurrence of a 7 and 10 days dry spells were 60% and 20% respectively in July (Figure 3.4). The length of growing season which is described as the difference between the onset and cessation tended to show a slight decreasing pattern over the last three decades (Table 3.5). During the extended dry season, mostly between October and January, the livestock are freely grazing on the crop residues. Thereafter, ample rainfall is required so that the woodlands and grasslands will start sprouting for a successful grazing by the livestock.

Table 3.5. Decadal mean onset and cessation of the rainy season from the perspectives of livestock keeping and maize farming in Langano, CRV of Ethiopia.

Land-use type	Decades (duration)	Mean date of onset	Mean date of cessation	Difference (cessation-onset, in days)
Maize cultivation	1981-1990	April 22	October 9	168
	1991-1990	May 9	October 3	143
	2001-2010	May 12	October 5	140
Livestock keeping	1981-1990	March 4	October 9	217
	1991-1990	February 22	October 3	220
	2001-2010	March 11	October 5	205

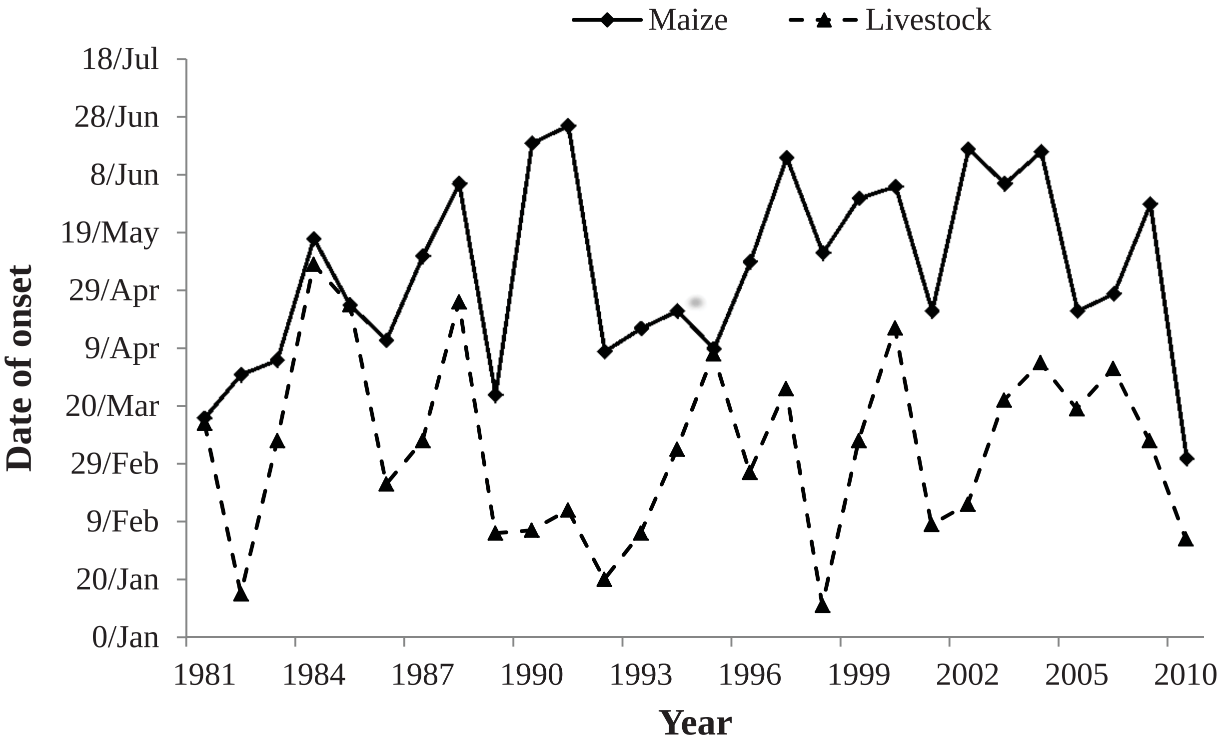

Figure 3.4. Onset of the rainfall season from the perspectives of maize cultivation and livestock during 1981 to 2010 (data not available for 2007 and 2008) in Langano, CRV of Ethiopia.

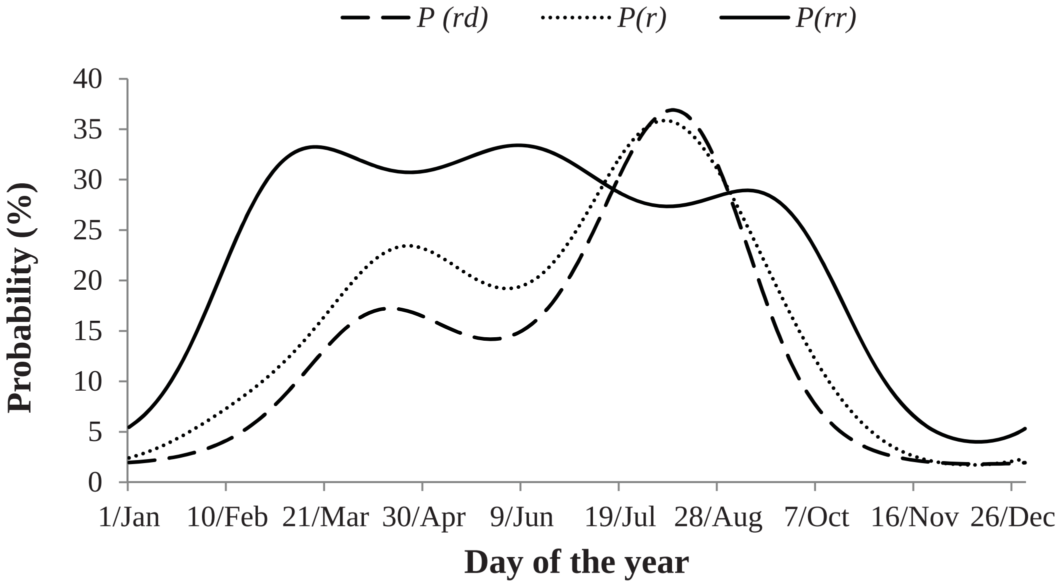

Figure 3.5. Probability of rainfall occurrence throughout the year (Pr)), probability of rainfall given the previous day was dry (P(rd)) and probability of rain given previous day received rain (P(rr)) in Langano, CRV of Ethiopia.

The results of drought vulnerability analyses of the two land-use types during the last three decades in Langano area is presented in Table 3.6. Drought vulnerability analyses based on the locally perceived criteria revealed that severe droughts affected livestock keeping during 25% (N=28) of the years due to extreme delay in the onset of rainfall after the extended dry season. Furthermore, moderate droughts that affected livestock productivity appeared during 32% of the years. On the other hand, maize cultivation was vulnerable to severe droughts during 25% of the years. While early cessation of the rainy season was observed only once (during 2002), late onset of the rainfall season and long dry spells during the critical growth stages of maize were mainly responsible for drought vulnerability of maize cultivation in the region. During late onset of the rainfall, sowing maize becomes a problem, and most farmers grow alternative crops such as haricot bean (*Phaseolus vulgaris* L.), Barley *(Hordeum vulgare)* and teff (*Eragratis teff*), despite their low productivity in the region.

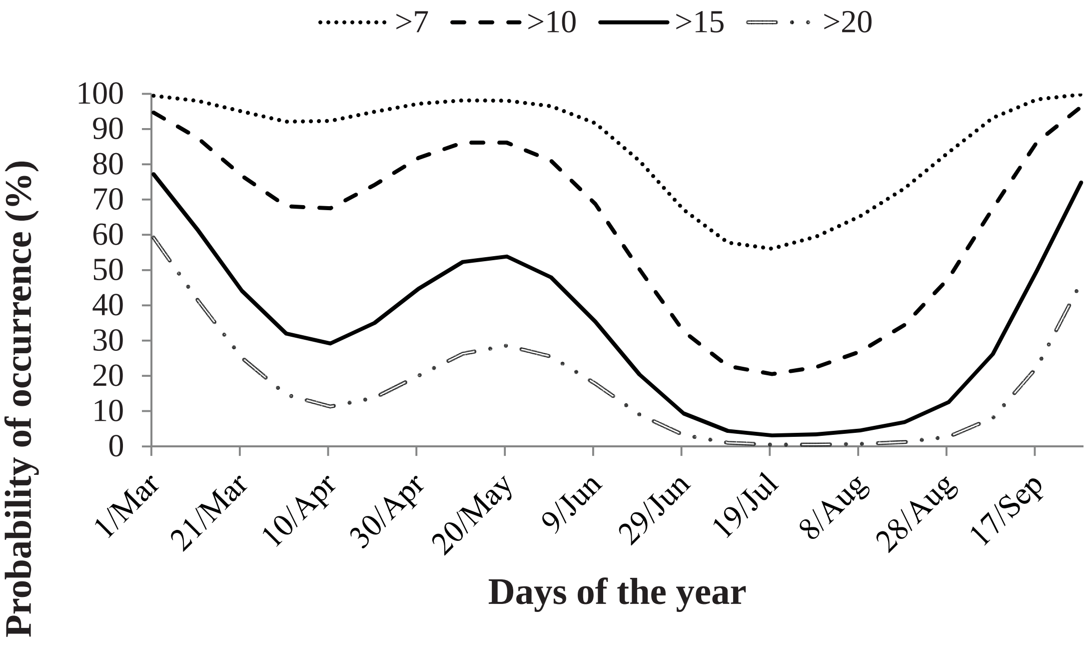

Figure 3.6. Probability of dry spells exceeding 7, 10, 15 or 20 days in Langano, CRV of Ethiopia.

Table 3.6. Drought vulnerability of maize farming and livestock keeping during the last three decades in Langano, CRV of Ethiopia

Criteria	Maize		Livestock	
	Years of severe droughts	Years of moderate droughts	Years of severe droughts	Years of moderate droughts
Due to late onset	1990, 1991, 1997, 2002, 2004	NA	1984, 1985, 1988, 1995, 2000, 2004, 2006	1981, 1983, 1987, 1994, 1997, 1999, 2003, 2005, 2009
Due to long dry spells after onset	1981, 2009	1982, 1987, 1995, 1996, 2001, 2006	NA	–
Due to early cessation	2002	NA	NA	NA
Percent out of total (N=28 years	25%	21%	25%	32.1%

'–', the criterion was no met; 'NA', criterion not applicable.

Having the maize-livestock mixed farming system, the local households were totally vulnerable to severe drought only once (2004) when both livestock and maize farming failed simultaneously while a pastoral way of life (livestock keeping only) was vulnerable to severe drought during 25% of the years. Mixed farming was vulnerable to moderate drought during 21% of the years while pastoral system was vulnerable to moderate drought during 32% of the years. Out of the 16 years when there were either severe or moderate droughts for livestock, only 8 years had rainfall amounts of 400-680 mm during the maize growing season. Hence, a drought year for livestock could still be a potentially productive year for maize cultivation. On the other hand, out of the 13 years when there were either severe or moderate droughts for maize, the 5 years were not drought for livestock revealing the advantage of mixed-farming over pastoral system for coping with drought.

3.3.3 The perceived drivers of land-use change

A range of environmental, socioeconomic, institutional, technological factors and access to markets were perceived by the local people as drivers for the observed changes in the land-use/cover in the study area. Therefore, the various factors are discussed under the three themes of: 1) Socio-economic and institutional changes, 2) Access to market and improved farming techniques, and 3) Drought vulnerability and the importance of mixed farming for survival.

3.3.3.1 Socio-economic and institutional changes

Based on the national censuses, the population of the study area was 2237 in 1984, 3219 in 1994, and 5369 in 2007 (CSA, 1996; 2008). Accordingly, the annual population growth rate was 4.4% between 1984 and 1994 and 5.1% between 1994 and 2007 which is greater than the national average of 3.2% (CSA, 2008). The higher population growth rate in the study area could be partly explained by the fact that a considerable proportion of the population is polygamous (30% of the respondents were married to 2-4 wives). Due to cultural reasons, the local men are married to women coming from remote areas mostly of the neighboring highland regions. Besides, there were some households (11% of the respondents) who migrated to the area from the densely populated highland areas. While the population between 1984 and 2007 increased by 2.4 times, the dense acacia coverage decreased from 27% in 1986 to 9% in 2010 and the area of cultivated land increased from 21% in 1986 to 29% in 2010. Hence, it is likely that population growth and the associated rise in the demand for cropland, grazing land and trees for household consumption and sale must have contributed to the observed land-use change. A majority (65%) of the respondents mentioned that they increased the size of their cultivated lands at the expense of woodlands and grasslands mainly in response to the increase in their family size. The young farmers (11% of the respondents) inherited their lands from their parents and once they had access to the woodlands and grasslands, they converted part of it to arable land. On the other hand, the rate of land-use conversion to cultivated lands decreased from 22 ha year^{-1} (during 1986-2000) to 18 ha year^{-1} (during 2000-2010) while the rate of population growth increased from 4.4% (between 1984 and 1994) to 5.1% (between 1994 and 2007). Hence, beyond population growth, other factors must also be affecting the observed land-use changes in the CRV.

The three time periods of 1965, 1986, and 2000 represented three different regimes of the Emperor, Socialist Derg and the current government, respectively. Land was owned by the feudal landlords until the change in government in 1974 that involved the 1975 land reform proclamation of "land for the tillers." The majority of the land owners (89% of the respondents) acquired their land from the government either during the Marxist Derg in 1975 or from the current government. The 110% increase in the area of cultivated lands from 1965 to 1986 implied the effect of change in government during 1974 and its new land reform proclamation. Severe forest losses have cropped up during and in the aftermath of government transitions. Huge losses of state-owned native forests following the change of the Marxist Derg to the present government in 1991 have been reported elsewhere (Bekele, 2003). A previous study in the southern Rift Valley of Ethiopia implied that the advent of cultivation in the overwhelming majority of the communities coincides with the creation of the peasant associations during the 1974 change in government, which formally endorsed private rights to croplands, as opposed to the (now) weakened authority of the traditional elders (Kamara et al., 2004). Although there were communal woodlands which were preserved during the previous two regimes, the majority of these communal lands were distributed to individual households since the last 15 years which might have contributed to the loss of the then dense acacia woodlands.

3.3.3.2 Access to markets and improved farming techniques

The losses of Acacia trees have been accelerated by the easy access to the CRV by those involved in charcoal enterprises (Figure 3.7). This is due to the highway connecting the capital Addis Ababa with Hawassa town and extends until Kenya through the CRV. It has been upgraded to a good quality asphalt road since 1995. More than 40% of the annual charcoal supply to the capital Addis Ababa is from the Rift Valley areas (Alem et al., 2010). Having very low ash content (4%) and the highest calorific value (7800 Cal g^{-1}), acacia trees are preferentially used for charcoal making in Ethiopia (Seboka, 2008). The selective cutting of *A. senegal* and *A. seyal* is evidenced by the low density of the mature trees in the CRV (Argaw et al., 1999). All the farmers (N = 66) have mentioned charcoaling and fuelwood selling as an important cause for the loss of acacia trees. It was understood from the accounts of elderly people that although charcoaling started in the area since the late 1960s, the extent of production and its perceptible effect on the loss of acacia trees is increasing over time. The increase in the area of scattered acacia woodlands while the dense acacia woodlands were decreased from 2000 to 2010 could be attributed to the increased cutting of acacia trees for charcoal making. Despite the on-going cutting of trees for charcoal making and fuelwood collection, it was difficult to determine the exact proportion of households who are practically involved in commercial charcoaling through the survey questionnaires in fear of prosecution. But all the respondents (N = 66) agreed that the number of people selling charcoal and fuel wood is the highest between June and August before harvesting of the next crop and during drought years. Thus, the price of charcoal decreases noticeably by then.

Figure 3.7. Charcoal making in the CRV of Ethiopia causing woodland degradation (Photo by Matthijs Kool, 2009).

Maize (*Zea mays* L.) being the staple crop (92% of the respondents had sown maize on all of their lands during the 2008 growing season), all of the respondents (N=66) would like to use the early maturing maize variety. According to the people's accounts, the introduction of early-maturing new maize cultivars improved crop productivity noticeably. Although the majority of the farmers used to apply broadcast sowing of maize (ICRA, 1999), recently line sowing has been adopted for it is suitable for better land management practices.

A range of improved land management techniques for better soil moisture conservation and improved productivity are being practiced by the local farmers (Table 3.7). The *Dirdaro* and *Shilshallo* techniques are being widely accepted in the Langano area. These techniques are used widely in other semi-arid areas of Ethiopia as moisture conservation techniques (Birhane et al., 2006; Nyssen et al., 2011). The *Dirdaro* furrow (ridge) is introduced to the area in association with the adoption of line sowing of maize. In this technique, ridges are made with the traditional Maresha plough after every two planting rows with an average interval of 50-54 cm across the slope. It helps to retain runoff and enhance infiltration. During the *Dirdaro* tillage, the soil from the ridges is inverted to both sides of the planting rows hence covering the soil moisture around the maize rooting zones from evaporation. About 35-45 days after planting, the *Shilshalo* ridging is also practiced with the traditional *Maresha* ploughing on the previously prepared *Dirdaro* furrows. In the Central Rift Valley of Ethiopia, where sandy loam soils are sensitive to crusting, *shilshalo* is a means of breaking the surface crusts and enhancing infiltration (Biazin et al., 2011a). According to the people's accounts, the low-lying areas that can receive runoff from the surrounding uplands are the most preferred for cultivation. Sowing is mostly done either early in the morning or late in the afternoon assuming that sowing during a hot sunny day could dry the soil immediately. Overall, the increased advantage from maize cultivation associated with increasing access to early-maturing cultivars and adoption of better land management might have contributed to the observed land-use conversion to crop cultivation.

Table 3.7. Farmers' perceptions of land management for improved water conservation in Langano area, CRV of Ethiopia.

Perception and opinion on land management	Proportion of total respondents (%, N=66)
Do you apply sowing of maize while tilling up and down in sloping cultivated fields?	
Yes	14
no	86
At what time of the day do you apply sowing of maize?	
Early in the morning or late in the evening	92
Any time of the day	8
Do you apply *Dirdaro* furrows during sowing of maize to reduce surface runoff and conserve moisture?	
Yes	67
No	33
Do you practice *Shilshalo* ridging 30-45 days following sowing of maize?	
Yes	100
No	0
The perceived major objective of *Shilshalo* ridging	
To break surface crusts and enhance infiltration	55
Remove weeds	24
Just to improve the maize yield	21
Do you apply shifting the location of corralling so that the fertilized land could be used for cultivation?	
Yes	41
No	59

3.3.3.3 Drought vulnerability and the importance of mixed-farming for coping

Currently, the majority of the people (97% of the respondents, N=66) are engaged in mixed farming systems – maize-based cultivation combined with livestock keeping. All the respondents (N=66) agreed that the mixed-farming system is less vulnerable to drought than the pastoral way of life in this drought-prone environment. Increased advantage from maize farming (41% of the respondents) associated with access to improved maize cultivars and the higher vulnerability of livestock to drought (49% of the respondents) were the primary perceived reasons for choosing mixed-farming over the pastoral way of life. Most of the local people (88% of the respondents, N=66) agreed that livestock rearing is more susceptible to drought than crop cultivation for it costs much time to recover from the loss of cattle. Cattle population recovery from drought is difficult either when there were greater die-offs due to a severe drought in a given year (Angassa and Oba, 2007) or when recovery phases are interrupted by new droughts (Oba, 2001). That is why the most severe drought years that caused major loss on livestock (such as 1984/1985) are more recalled by the local people than those drought years for maize farming when the farmers still may get some yield after replanting the fields with haricot bean, teff or barley. The old custom of migrating temporarily with livestock further to the neighbouring areas during drought (locally known as *Godantu*) is not possible anymore, except for 5% of the respondents who are still temporarily migrating. Grazing areas in the neighbouring highlands have been dramatically converted to crop cultivation (Garedew et al., 2009). Goats (58% of respondents) and donkeys (42% of the respondents) were mentioned as the least sensitive animals to drought in the study area while browsing on the remaining acacia trees. However, the local people complained that goats are easily predated by foxes while children who used to herd them are now going to school with increased access to education. Thus, the dependence on the income from goats is decreasing (67% of the respondents).

Livestock rearing and maize cultivation complement each other - oxen are used to plough the land and crop residues can be used as fodder for the livestock during the extended dry seasons. According to the respondents, major purposes of the livestock are draught power (57%), milk and related dairy products for household consumption (31%), and income from sale (12%). Livestock grazes on the grasses and the leaves of acacia trees throughout the year and on crop residues following crop harvest. When there is no enough rainfall to grow grasses until the beginning of April, when the farmers mostly apply the first tillage, oxen might not be strong enough to plough the land in time. On the other hand, poor farmers who lack oxen to plough their land are not always able sow maize in time. Hence, they are mostly dependent on sharecropping arrangements with other farmers and they are, therefore, more vulnerable to drought. Although a large number of livestock is the sign of prestige or assumed as an asset, farmers may be forced to sell their livestock and buy food to rescue their families during times of severe food shortage. All the respondents (N=66) wanted to retain as much grazing land as possible and continue with the mixed farming system.

Drought coping strategies are different amongst the different classes of farming households (Table 3.8). Being a poor or rich farmer is not only a matter of differences in the amount of livestock, land and money, but also leads to differences in drought perceptions, use of networks and coping strategies (Kool, 2010). Rich households perceived the occurrence of drought every 7-10 years while the poor farmers perceived it within a range of 3 -5 years. This could imply that rich farmers are affected mainly by severe droughts for livestock that occurred once in 7 years on average. Similarly, the perception of the poor to drought frequency is in line with the meteorological analyses that revealed the occurrence of moderate drought once in 3-4 years. While the non-agricultural coping strategies (selling of forest products, sand mining and external aid) are important for many of the poor and medium class households, the rich households are mainly dependent on selling of their livestock and adjusting their agricultural management with drought. During the 2008 drought when this study was being undertaken, 48% of the respondents most of whom are rich tried to survive the risk of drought for livestock by selling some of their cattle. On the other hand, when there is a failure of early sown maize due to long dry-spells, farmers may replant haricot bean or teff although these crops may still suffer from drought at flowering and grain-filling stages. Relief aid has been channeled to the area since the 1970s (District office of Agriculture, personal communications). During the 2008 cropping season, more than 15% of the respondents, mostly poor, received relief aid from governmental and non-governmental organizations.

Table 3.8. Primary coping strategies to recurrent drought and its relation to wealth category, in the CRV, Ethiopia.

	Proportion of total respondents (%, N=33)		
Coping strategies	Poor	Medium	Rich
Selling of livestock	9	27	13
Selling of forest products (charcoal and fuel wood)	18	12	0
Relief aid	12	3	0
Selling sand	3	3	0

3.4 Discussion and Conclusion

The central Rift Valley drylands around the lakes had been covered with dense acacia-based woodland which was used by the pastoral Oromo people. However, the situation has been changing over the last five decades when the pastoralists became more sedentary (Eshete, 1999; Mohammed, 1993). A substantial land-use change has been observed in the region since 1965. The striking conversion from woodlands and grasslands to cultivated lands during the period between 1965 and 1986 could be mainly attributed to the change in government during 1974 and its new land reform proclamation of “land for the tillers.” The change in the land tenure system might have also weakened the valuable indigenous institutions of pastoral communities that were maintained for centuries (PFE, 2010). However, while it has still continued, the rate of land-use conversion to cultivated lands during the period between 1986 and 2010 has slowed (Table 3.8). This could be attributed to the fact that the local farmers (100% of the respondents) wanted to retain as much grazing land as possible and continue with the mixed farming system. In the other parts of the Ethiopian Rift Valley, the changes from native vegetation to crop cultivation continued until the forest cover was below 5% (Dessie and Kleman, 2007: Garedew et al., 2009). A factor in this may be that the distribution and amount of precipitation is by far better for growing crops in the south Central Rift Valley of Ethiopia (Dessie and Kleman, 2007) than the CRV where this study was undertaken. Furthermore, in the other parts of the Rift Valley drylands, some portions of the arable lands could be used for irrigated crops due to better access to perennial streams draining from the neighbouring highlands (Dessie and Kleman, 2007; Garedew et al., 2009).

Increasing changes from dense woodland cover to scattered acacia cover have been observed even in recent decades. This could be mainly attributed to the selective cutting of acacia trees for charcoaling and fuel wood. The Rift Valley woodlands being the main source of charcoal for the growing demand in the capital Addis Ababa (Alem et al., 2010), selective cutting of A. Senegal, and A. seyal has been exacerbated due to their good quality charcoal. Particularly, during drought years when livestock or maize productivity is decreased or a total failure, the local people are dependent on selling of charcoal and fuel wood as an immediate source of income until external food aid and other employment opportunities are available.

The shift from a predominantly pastoral way of life to a crop-livestock mixed farming system has been considered as a better strategy for coping with recurrent drought. The analyses of drought based on long-term meteorological data confirmed the credibility of the people's perception regarding drought vulnerability – mixed farming is more reliable than pastoral way of life for coping with recurrent drought. The mixed farming system was vulnerable to severe drought only during 4% of the years (once out of twenty eight years) while the pastoral way of life was vulnerable to severe droughts during 25% of the years. Even in the well-known pastoral areas of the southern Rift Valley around Borena, recurrent drought and the consequent loss of livestock has forced pastoralists to take up crop cultivation as a supplementary source of income (PFE, 2010). Coping with recurrent drought and rainfall uncertainty through farm diversification has also been reported elsewhere (Cooper et al., 2008; Flueret, 1986). The steady reduction in the cattle population and calving rates during drought years confirmed the vulnerability of pastoral life and the difficulty to recover for the following years (Angassa and Oba, 2007). This could be even worse particularly when recovery phases are interrupted by new droughts (Oba, 2001). The recent drought (2011) which put more than 12 million people under famine mainly in pastoral areas of eastern Africa including Ethiopia has been caused by the failure of two consecutive rainfall seasons that caused a severe loss of livestock due to lack of recovery phases (FEWSNET, 2011).

Recurrent drought has been caused either due to the late onset of the rainfall seasons (both for livestock and maize farming) or extended dry-spells after onset that mainly affects crop cultivation. More than half of the drought years for livestock were good years for maize due to sufficient amount of rainfall during the maize growing period. On the other hand, 38% of the drought years for maize were suitable for livestock. For the early maturing local maize varieties that are harvested within 3-4 months, the best sowing time could be between the mid of April and beginning of June. Hence, the maize crop will have a better probability of escaping long dry spells (> 15 days) during the first 60 days after sowing and short dry spells (> 7 days) during the flowering and maturing stages. Although there was no perceptible trend in the cessation of the rainy season, there was a trend of delay with the onset of the rainy season for both livestock and maize farming in the region. Maize cultivation being susceptible to different lengths of dry spells, a range of improved land management and rainwater harvesting techniques has been adopted in the CRV (Table 3.7).

The higher rate of population growth in the CRV as compared to the national average during the last three decades could be associated with the culture of polygamy and immigration to the CRV. Culturally, marriage is made between people of different clans that let the local men to bring their respective wives from remote highland areas. Consequently, the burgeoning population might have exacerbated the pressure on woodlands either due to increasing demand for more cultivable land or charcoaling and fuel wood selling particularly during drought years. The combined effect of drought and migration on land-use conversion has been previously implied (Reid et al., 2000; Tsegaye et al., 2010). Droughts during the 1970s and early 1980s in Northern Ethiopia have caused an influx of migrants to south western Ethiopia where the immigrants initiated land-use change to cultivation (Reid et al., 2000). According to Tsegaye et al. (2010), drought events during 1973/74 and 1984/85 forced influx of migrants from the neighbouring Tigray to the northern Rift Valley dry lands of Ethiopia where the immigrants have initiated land-use conversion to crop cultivation due to free access to cultivable lands. However, population increment due to migration to the CRV may be less likely in the future for two reasons: 1) There is less access to land by the immigrants as most of the communal lands (except the non-arable land around the lake shores) are owned by individual households, and 2) Polygamy is also less likely as the new farmers are not willing to have more than a wife.

The long-term effects of converting woodlands and grasslands to cultivation in the Ethiopian Rift Valley areas could have negative environmental and socioeconomic consequences unless improved and sustainable land management techniques are introduced. The long-term use of the traditional Maresha cultivation after conversion from acacia-based grasslands revealed deterioration of soil physical properties (Biazin et al., 2011a). Moreover, the Ethiopian Rift Valley is home to an important chain of lakes, and increasing threats have been observed on the hydrological and biological features of these lakes in association with land degradation and deforestation of the surrounding areas (Ayenew, 2004; Legesse and Ayenew, 2006). It is important to realise that restoring degraded drylands to good condition will not happen amenably because the costs of doing so exceed benefits (Bojo, 1996; Dregne, 2002). Thus, sustaining the rainfed agriculture through improved techniques, such as rainwater harvesting and management (Biazin et al., 2011b), while concurrently applying improved livestock management approaches may help to mitigate further degradation of the remnant woodlands in this drought-prone region.

Furthermore, sustainable management of the woodlands and grasslands could contribute to the global efforts of carbon sequestration enhancements. Upon a review of research results in SSA about carbon sequestration amid the on-going land cover changes, Vagen et al. (2005) revealed that soil carbon content is generally higher under trees compared to cultivated lands in savannah ecosystems. The total net emission of carbon from tropical deforestations indicates a major global warming impact from tropical land uses, equivalent to approximately 29% of the total anthropogenic emission from fossil fuels and land-use changes (Fearnside, 2000). Linking forest management to the carbon market has the potential to significantly decrease the price of carbon and to alleviate the policy burden of energy and climate change (Tavonia et al., 2007). Because the carbon sink capacity of the world's agricultural and degraded soils is 50-66% of the 42-78 Giga tons of carbon loss over the years, soil restoration and woodland regeneration, no-till farming, cover crops, nutrient management, manuring and sludge application, improved grazing, water conservation and harvesting, are being recommended to improve organic carbon sequestration in the dry tropics (Lal, 2004; Reid et al., 2004).

Generally, this study implied that the acacia-based woodlands have been steadily converted to cultivated lands, scattered acacia and grasslands due to the interplay of biophysical and socioeconomic drivers. Drought being a priority challenge for the burgeoning local population amid institutional dynamics, coping with recurrent drought either by shifting to maize-livestock mixed farming or direct cutting of acacia trees for charcoal selling has exacerbated the loss of woodlands. The same trend of land-use/cover change tends to happen in the rest of the vast Ethiopian Rift Valley where a pastoral way of life is still present. Thus, appropriate policy and technological interventions are required to develop appropriate drought adaptation and mitigation strategies in order to avert the increasing degradation of woodlands in this drought-prone region.

Chapter 4

The effect of long-term *Maresha* ploughing on soil physical properties in the Central Rift Valley of Ethiopia

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The effect of long-term Maresha ploughing on soil physical properties in the Central Rift Valley of Ethiopia

Abstract

For thousands of years, smallholder-based crop farming in Ethiopia has been practiced with oxen ploughing using the traditional *Maresha* ard plough where consecutive tillage operations are undertaken perpendicular to each other. Despite its wide acceptance by smallholder farmers, long-term use of the *Maresha* is believed to deteriorate the soil's physical properties. This study examines the surface and subsurface infiltration, soil evaporation and penetration resistance of sandy loam soils that have been exposed to varying durations (0, 2, 7, 22 and 35 years) of cultivation after being converted from acacia-based grassland dominated by *Acacia tortilis* and *Acacia senegal* in the Central Rift Valley (CRV) of Ethiopia. The infiltration rate of the surface layer increased significantly ($p = 0.05$) immediately after conversion from acacia-based grassland to cultivated land. Thereafter, there was a weak decreasing trend ($p > 0.05$, $R^2 = 0.24$) in infiltration rate with years of cultivation. Unlike the surface soil layer, there was no significant difference in the subsurface (below 15 cm) infiltration between the acacia-based grassland and lands cultivated for varying numbers of years. Following a rain event satisfying field capacity of the soils, the daily soil evaporation increased significantly ($p = 0.05$) with increased duration of cultivation. The cumulative evaporation, observed over five consecutive days following the last rainfall, increased by 2.4 times in the 35 year old cultivated land from the acacia-based grassland. There was also a strong correlation ($R^2 = 0.86$) between α (the slope of the cumulative evaporation versus the square root of time) and an increase in the years of cultivation. It is, therefore, concluded that long-term *Maresha* cultivation along with the present soil management makes the maize crop susceptible to drought and dry-spells. Improved soil management and development of appropriate tillage are needed to maximize rainwater use efficiency and achieve a more sustained agricultural production in the drought-prone CRV of Ethiopia.

4.1 Introduction

Soil tillage is an important agricultural activity because of its impact on crop production and soil properties (Chatterjee and Lal, 2009; Chivenge et al., 2007; Lal, 2009). A literature review of the impact of different tillage techniques on soil physical properties showed no constant trends (Strudley et al., 2008). Although the effect of no-till farming is found very important to improve the soil physical characteristics (Alvarez and Steinback, 2009; Lal, 1997; Strudley, 2008), appropriate and improved tillage practices have been recommended to improve the soil hydraulic characteristics of crusting tropical soils (Hoogmoed, 1999; Temesgen, 2007). In Eastern Africa, the performance of different tillage techniques varied with soil type, climate characteristics and farming systems (Biamah et al., 1993). Tillage impacts are generally more pronounced in marginal soils and harsh environments than in inherently fertile soils of high resilience and favourable micro- and meso-climates (Aboudrare et al., 2006; Lal, 2009).

The arid, semiarid and dry sub-humid lands of Ethiopia occupy approximately 65% of the total land mass (close to 700,000 km^2) of the country (EPA, 1998) and 46% of the total arable land (Yonas, 2001). In response to the steadily increasing population and a decreased productivity in the Ethiopian highlands, the low-lying drylands are being increasingly cultivated at the expense of native forests and woodlands. The Central Rift Valley (CRV), as part and parcel of the vast Ethiopian drylands, is being rapidly converted from acacia-based grassland into cultivated land (Dessie and Kleman, 2007; Rembold et al., 2000). However, the smallholder-based traditional rainfed cultivation practices in these areas are believed to deteriorate the soil's capacity to support human life sustainably.

For thousands of years, the Ethiopian farmers have been using a traditional tillage implement, called *Maresha*, which is commonly drafted by oxen (Aune et al., 2001; Gebregziabher et al., 2006). Because of incomplete, V-shaped ploughing by the *Maresha*, farmers have to do repeated tillage with any two consecutive tillage operations carried out perpendicular to each other. As a result, the soil is excessively pulverized resulting in poor soil structure and crust formation (Temesgen, 2007). Farmers plough 2 - 4 times before sowing maize in the CRV. Furthermore, a traditional ridging practice, locally known as *Shilshalo*, is conducted after planting using the oxen-drawn *Maresha* plough mainly to break the surface crusts (Figure 4.1). Several factors can affect the frequency of tillage. A study in the semi-arid Ethiopian Rift Valley revealed that tillage frequency increased with the education level and experience of farmers, their perception about the purpose of tillage, and with resource availability such as area of land, number of oxen and family labour (Temesgen et al., 2008). Many farmers mentioned moisture conservation, weed control and soil warming as purposes for repeated tillage (Temesgen et al., 2008). Because of repeated tillage at shallow depths, commonly between 13 and 16 cm, plough pans may form below the plough layer. The V-shaped furrows also result in higher relative surface area exposure leading to an increased loss of moisture through evaporation (Temesgen, 2007). However, little is known about the dynamics of soil physical properties in response to long-term traditional *Maresha* ploughing in the CRV.

The objective of this study was, therefore, to examine the dynamics of soil physical properties (mainly infiltration, soil evaporation and penetration resistance) following conversion of acacia-based grassland to cultivated land and long-term *Maresha* ploughing in the sandy loams of the CRV of Ethiopia. Changes in physical soil properties were compared between lands cultivated for different numbers of years and the adjacent acacia-based grasslands with similar inherent soil properties. The trends of the changes were then used to estimate the impacts of traditional *Maresha* cultivation on these soil properties, and as indicators for the sustainability of the existing cultivation system in this drought-prone region.

Figure 4.1. The traditional Shilshalo ridging practiced using the Maresha at three days after a rain event to break the surface crusts between rows of maize in the central Rift Valley of Ethiopia (Photo by Birhanu Biazin, July 2008).

4.2 Materials and methods

4.2.1 Site description

The study site is located around Langano ($38^{0}40$ E, $7^{0}33$ N) in the CRV of Ethiopia, which is situated about 190 km south of the capital, Addis Ababa (Figure 4.2). The average slope is 0-2% and the altitude is about 1600 m.a.s.l. The mean annual rainfall is 650 mm with a coefficient of variability of 30%. Mean annual evapo-transpiration reaches 1700 mm. The geological and geomorphologic features of the region are the result of Cenozoic volcano-tectonic and sedimentation processes having several shield volcanoes developed over large parts of the adjacent plateaux (Ayenew, 2007). The soil is classified as Haplic solonetz with a texture ranging between loamy sand to sandy loam (Itanna, 2005) that readily compacts and is susceptible to crusting, and also sensitive to drought.

Although the area was previously covered by dense acacia woodlands which had been used by the pastoral Oromo people coming from the nearby highland areas (Eshete, 1999), the woodlands have been steadily converted to a sedentary and subsistence mixed farming system that encompasses crop cultivation and livestock farming. A substantial change from the dense woodlands to scattered acacia-based grasslands has occurred over the last four decades (Mohammed, 1993; Rembold et al., 2000). Currently, a significant proportion of the area is subjected to cultivation and grazing. The tree cover consists of remnants of acacia species scattered in the landscape. Acacia species such as *Acacia tortilis*, *Acacia senegal, Acacia seyal,* and *Acacia etbaica* are present in the grazing lands and remnants of these are also in the cultivated land. The losses of Acacia trees have been accelerated by the easy access to the CRV by persons involved in charcoal enterprises along the highway in the area. The selective cutting of *A. senegal* and *A. seyal* is evidenced by the low density of the mature trees (Argaw et al., 1999). Major crops grown in the CRV are maize (*Zea mays* L.) and haricot bean (*Phaseolus vulgaris* L.). Livestock includes mainly goats and cattle. Most grazing is free roaming throughout the year. Following crop harvests, livestock freely graze on the crop residues. Cattle manure is rarely used on cultivated fields and the households that were considered for this study did not put any manure on the studied fields.

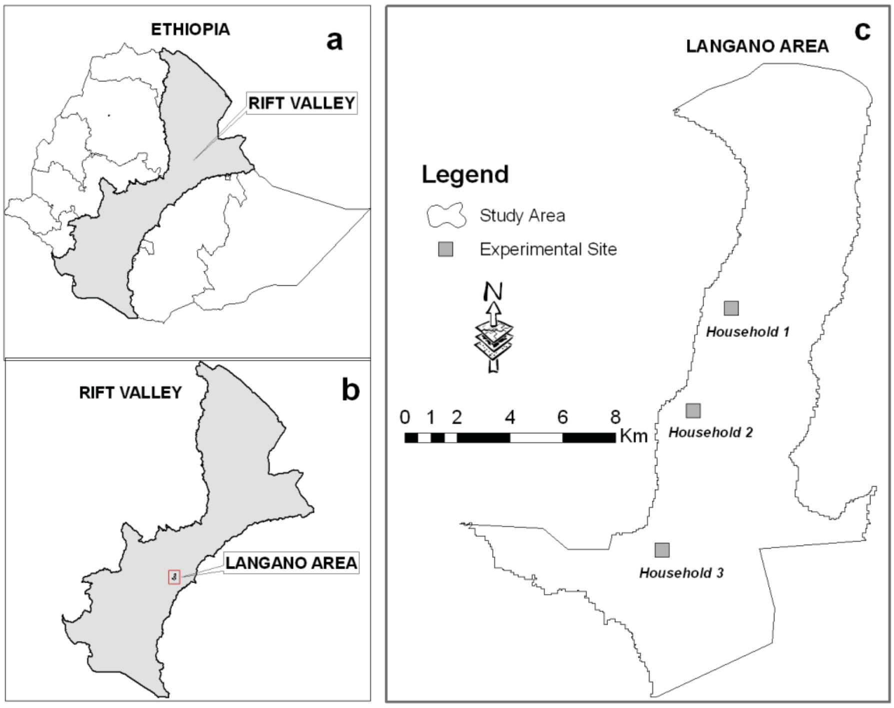

Figure 4.2. Location map of the Rift Valley in Ethiopia (a), of the Langano area in the Rift Valley (b), and of the three selected households in the Langano area (c).

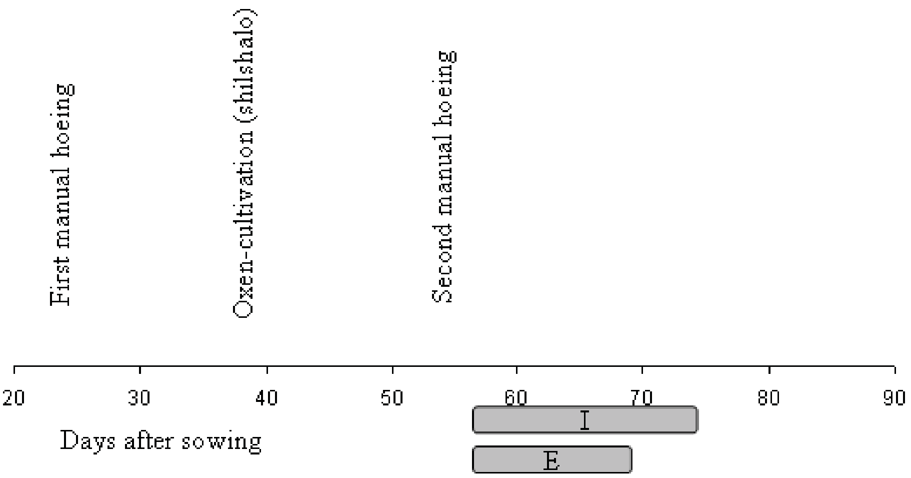

Figure 4.3. Timing of field measurements of infiltration (I) and soil evaporation (E) after the second manual hoeing at Langano, Ethiopia. Timeline of farm operations are counted according to the days after sowing of maize.

4.2.2 Methods of sampling and data collection

Three different households, who have been cultivating maize after chronologically converting more of the acacia-based grasslands, were selected (Figure 4.2). Each household converted the acacia-based grasslands to cultivated fields in 1973, 1986, 2001 and 2006 implying 35, 22, 7 and 2 years of cultivation respectively up to our sampling in 2008. The adjacent acacia-based grasslands were characterised by sparse acacia tree covers (an average of 10 % canopy cover) and with extensively grazed grass undergrowths. These grasslands were considered as the control plots in our experiment. The main criteria for selection of these three households were the similarities in the inherent characteristics of their fields, the similarities of their previous cropping and land management practices and their proximity to each other. The households that were considered for this study never applied any manure or chemical fertilizer on the fields. Like most other farmers in the CRV, they cultivated haricot bean the first year after conversion of the acacia-based grasslands to cultivation. Thereafter, they cultivated maize mono cropping continuously. They always apply *Maresha* ploughing 3-4 times until sowing, and the traditional *Shilshalo* practice 35-40 days after sowing of maize. They also apply first manual hoeing two weeks after sowing of maize and second manual hoeing in two weeks after the *Shilshalo* practice. They have never harvested the crop residues. Between the harvest of the previous crop and the next sowing, all of them allowed free grazing of their livestock on the cultivated fields. Following soil sampling and analysis of selected properties, measurements of surface and sub-surface infiltration, soil evaporation, and penetration resistance were undertaken on the cultivated plots and in the adjacent grassland. Based on the timeline of farm operations during the maize growing season in 2008, measurements of infiltration, soil evaporation and penetration resistance were undertaken after the second manual hoeing (Figure 4.3).

4.2.2.1 Soil sampling and analysis

Soil samples were taken from the surface layer (0-15 cm) in each of the farmers' fields representing the different number of years of cultivation. The first 0-15 cm soil layer is assumed to be the average plough depth of the *Maresha* in the CRV. A total of 45 samples (4 cultivation durations plus the acacia-based grassland x 3 households x 3 replicates) were taken. Soil texture analysis was done using the hydrometer method (Gee and Bauder, 1986). The percentage organic carbon was determined by the Black and Walkley method (Allison, 1965). Forty-five undisturbed core samples were also collected from surface soils (0-15 cm) under all cultivation durations and oven dried at 105°C to determine the soil bulk density. The gravimetric soil water content was determined from the 45 soil samples that were collected from the surface soil (0-5 cm) just before the measurement of penetration resistance and microlysimetric evaporation.

4.2.2.2 Surface and subsurface infiltration

Infiltration measurements were undertaken at the soil surface and below the plough layer (subsurface soils) in the acacia-based grassland and in the fields with varying durations of cultivation. The subsurface infiltration was determined after carefully removing the top 15 cm of soil. Infiltration rate was determined in triplicate using double-ring infiltrometers (Bertrand, 1965). The inner rings had diameters of 28, 30 and 32 cm and the outer rings 53, 55 and 57 cm. The rings were driven approximately 5 cm into the soil. The cylinder was refilled to the 20-cm level each time the head of water decreased to 5 cm above the soil surface. Changes in the water level were recorded at 1, 3, 5, 10, 15, 30, 45 and 60 minutes after the start of the infiltration measurement. A total of 45 measurements (4 cultivation durations plus the acacia-based grassland x 3 farmers' fields x 3 replicates) were done for the surface infiltration and another 45 for the subsurface infiltration studies.

4.2.2.3 Soil evaporation

Daily soil evaporation was measured using micro-lysimeters that were 150 mm long with 100 mm internal diameter. The use of the micro-lysimeter method for semi-arid tropics was discussed by Daamen et al. (1993). The length of the micro-lysimeters was made similar to the average ploughing depth with the *Maresha*. A total of 60 micro-lysimetric measurements (4 cultivation durations plus the acacia-based grassland x 3 households x 4 replicates) were taken. Microlysimeters were installed in pairs, one close to the rows and the other in mid-row uniformly (Daamen et al., 1993; Daamen et al., 1995). Soil cores were extracted following rain events that satisfied the field capacity of the surface soils and weighed every morning for 5 consecutive days (Bonsu, 1996) when there was no addition of any rainfall. Daily weight differences were converted into evaporation (E_a) using equation 4.1.

$$E_a = 10\frac{\Delta W}{\rho_w A} \qquad [4.1]$$

Where:
E_a [mm d^{-1}] is daily soil evaporation,
ΔW [g d^{-1}] is the change in sample weight,
10 is used to convert cm to mm,
ρ_w [g cm^{-3}] is density of water, and
A [cm^2] is the cross sectional area of the micro-lysimeter that was actually 78.57 cm^2.

Cumulative evaporation at any stage of the crop development since the last rain event was found to be proportional to the square root of time following each heavy rainfall (Black et al., 1969; Boesten and Stroosnijder, 1986). Accordingly, equation 4.2 was used to characterise the dynamics of soil evaporation since the beginning of each drying cycle.

$$\sum E = \alpha t^{1/2} \qquad [4.2]$$

Where:
ΣE is cumulative evaporation (mm) till day t,
t represents the days after the last rain event, and
α represents the slope of a linear regression fitted to the points.

Thus, t = 0 implies the end of the previous rain that satisfied field capacity of the soils. Based on the regression from each "years of cultivation" duration, the correlation between the slope (α) of each regression and cultivation duration was determined. This was used as an indicator of the dynamics of soil evaporation with cultivation durations.

4.2.2.4 Penetration resistance

The penetration resistance of the soils was determined using a digital penetrologger (Eijkelkamp Equipment, Model 0615-01 Eijkelkamp, Giesbeek, The Netherlands) which had a cone angle of 30^0 and a base area of 1 cm^2. It was carefully inserted into the soil profiles in 1 cm increments from the surface to a depth of 25 cm by the same person following a rain event that satisfied the field capacity of the soils.

4.2.3 Data analysis

Statistical analyses were done using the SPSS version 15.0 for windows (Julie, 2007). Analysis of variances (ANOVA) was made using the General Linear Model (GLM) Univariate procedure. When there were statistically significant differences ($p = 0.05$) between the variables, Tukey's honestly significant difference test for equal variances and Dunnett's T3 test for unequal variances were used for mean separation. Pearson's correlation was also employed after screening outlying data points.

4.3 Results

4.3.1 Soil properties

There were no significant ($p = 0.05$) differences in sand and clay textural classes between the different cultivation durations for the surface soils (Table 4.1). The fraction of silt in the surface soils showed significant differences ($p = 0.05$) between the different cultivation durations although no clear trend was observed. Overall, texture of the surface soils ranged from sandy loam to loam with a clear similarity in all the studied locations. Bulk density and percentage organic carbon showed no significant differences ($p = 0.05$) between the various cultivation durations within the sampled depth.

Table 4.1. Soil properties of the surface layer (0-15 cm), which is the plough layer, in acacia-based grasslands (0) and soils under cultivation for 2, 7, 22 and 35 years in Langano, Ethiopia.

Cultivation duration (yrs)	Sand (%)	Silt (%)	Clay (%)	Bulk density (g cm^{-3})	Organic carbon (%)
0	56.0 (2.0)a	27.0 (3.0)ab	17.0 (1.0)a	1.18(0.20)a	1.99 (0.40)a
2	46.0 (4.5)a	32.0 (0.5)a	22.0 (4.0)a	1.11(0.01)a	1.98 (0.20)a
7	49.5 (3.5)a	30.5 (0.5)ab	20.0 (4.0)a	1.14(0.08)a	2.22 (0.35)a
22	44.5 (2.5)a	31.5 (0.5)a	24.0 (2.0)a	1.18(0.03)a	1.97 (0.17)a
35	59.0 (1.0)a	23.5 (0.5)b	17.5 (0.5)a	1.17(0.02)a	1.85 (0.23)a

Standard error of the mean in parenthesis and mean values followed by similar letters along columns are not significantly different (p=0.05) with respect to cultivation durations.

4.3.2 Infiltration rate

Infiltration rate of the surface soils increased significantly ($p = 0.05$) two years after the conversion of acacia-based grassland into cultivation (Figure 4.4). It increased by 49% after 1 minute, 41% after 10 minutes, and 33% after 30 minutes. However, there were no significant differences ($p = 0.05$) in the surface infiltration between the acacia-based grassland and the land that had been cultivated for 7 years or more. Though not significant ($p > 0.05$), there was a weak decreasing trend ($r2$) = 0.24) in infiltration rate with increased years of cultivation from 2 to 35 years. For instance, the infiltration rate in the 35 years cultivated land was lower than that of the 2 years cultivated land by 30% after 1 minute and 31% after 10 minutes.

There were no significant differences (p = 0.05) in infiltration rate in the subsurface soils of the acacia-based grassland and lands cultivated for varying numbers of years. However, as with the surface soils, a weak decreasing trend was observed as the years of cultivation increased from 2 to 35 (Figure 4.4).

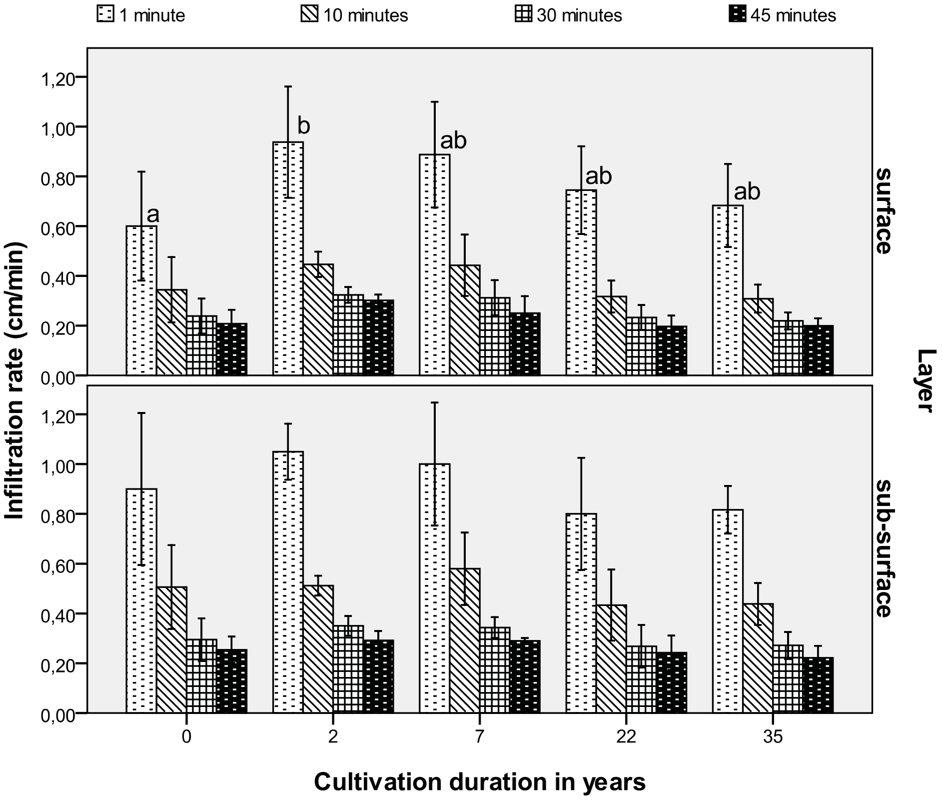

Figure 4.4. Infiltration rate of surface and sub-surface layers (below 15 cm) in the acacia-based grasslands (0), and cultivation durations of 2, 7, 22 and 35 years in Langano, Ethiopia. Error bars represent standard error of the mean. Bars of similar patterns depicted by similar letters are not significantly (p = 0.05) different with increase in cultivation durations. Bars of similar patterns that are not followed by any letter are meant also not significantly different.

Looking at infiltration rate over time within the various plots, the infiltration rate of the surface soils in all the cultivated plots decreased significantly (p = 0.05) after 10 minutes, while a significant decrease in the acacia-based grassland only occurred after 30 minutes. There was no significant difference (p = 0.05) in the infiltration rate of the subsurface soils with time amongst the acacia-based grassland and various cultivation durations.

4.3.3 Evaporation

Daily soil evaporation was significantly different (p = 0.05) for the various cultivation durations in the first two consecutive days following a rain event satisfying field capacity of the soils (Table 4.2). The actual daily evaporation increased by 2.41 times (one day after the preceding rainfall) and 2.56 times (two days after the preceding rainfall) in the plots cultivated for thirty five years compared to the acacia-based grassland. Similarly, compared to the acacia-based grassland, the five days cumulative evaporation in the plots converted thirty five years ago increased by 2.3 times and by 37% in the two year old fields.

Based on observations for five consecutive days, the values of α (slope) were 2.38 (R^2 = 0.97) for grassland soils and 3.44 (R^2 = 0.99) for 2 years cultivated soils, 3.90 (R^2 = 0.93) for 7 years cultivated soils, 3.99 (R^2 = 0.99) for 22 years cultivated soils, and 5.72 (R^2 = 0.98) for 35 years cultivated soils (Figure 4.5). Hence, the resultant relationship between the slope and cultivation durations showed a strong correlation (R^2 = 0.83; Figure 4.6).

Table 4.2. Soil evaporation (mm d^{-1}) from the acacia-based grassland (0) and cultivation durations of 2, 7, 22 and 35 years in Langano, Ethiopia

Cultivation duration (years)	Soil water content (m^3/ m^3)†	Evaporation (mm d^{-1}) since the last rain event				
		1^{st} day	2^{nd} day	3^{rd} day	4^{th} day	5^{th} day
0	0.27 (0.02)a	2.01(0.33)a	1.20(0.11)a	0.86(0.07)a	0.82(0.12)a	0.62(0.09)a
2	0.24 (0.02)b	3.16(0.52)ab	1.66(0.22)a	1.12(0.11)a	1.03(0.15)a	0.84(0.12)a
7	0.25 (0.01)ba	3.14(0.58)ab	1.91(0.27)a	1.40(0.15)a	1.26(0.18)a	1.10(0.13)a
22	0.27 (0.02)ca	3.61(0.57)bc	2.00(0.18)a	1.34(0.09)a	1.14(0.11)a	0.90(0.07)a
35	0.32 (0.03)d	4.88(0.52)c	3.07(0.19)b	1.91(0.11)a	1.84(0.11)a	1.72(0.06)a

Values followed by similar letters (a–c) in columns are not significantly different (p = 0.05) with respect to cultivation durations. † *The soil water content was measured from the top 0-5 cm soil layer of the various cultivation durations just before the measurement of evaporation.*

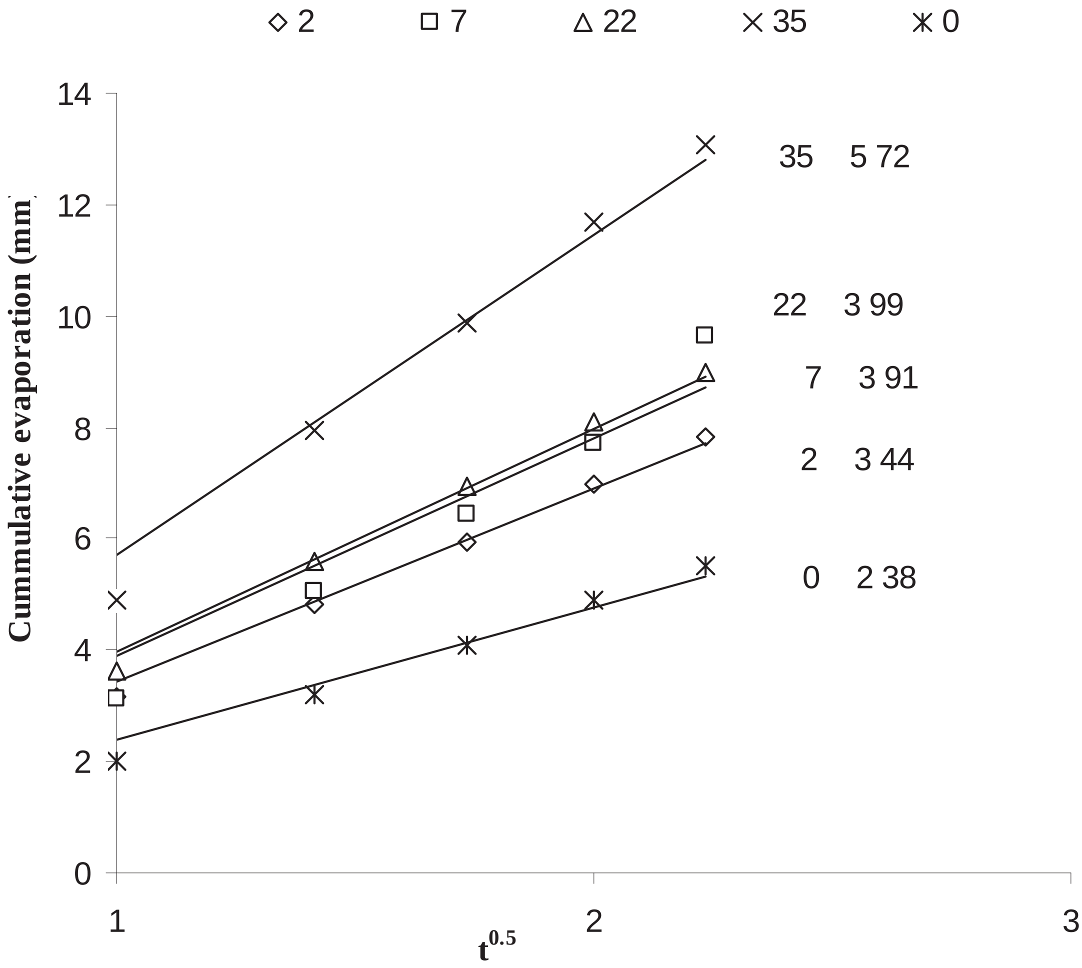

Figure 4.5. Cumulative soil evaporation (mm) from the acacia-based grasslands (0), and cultivation durations of 2, 7, 22 and 35 years in Langano, Ethiopia. The time (t) represents the five consecutive days since the last rainfall.

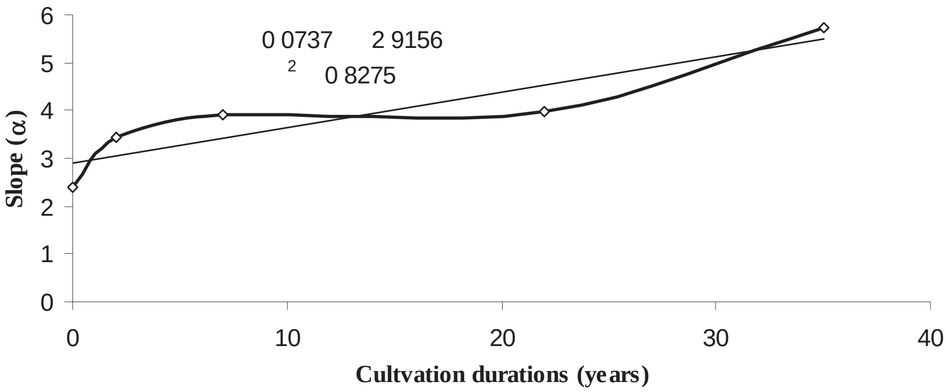

Figure 4.6. Relationship between the α (the slope of the cumulative evaporation versus the square root of days since the last rain) and the cultivation durations in Langano, Ethiopia.

4.3.4 Penetration resistance

Penetration resistance (PR) of the acacia-based grassland was significantly (p=0.05) higher than that of the cultivated fields in the top 8 cm soil depth (Table 4.3). PR significantly increased with depth (1-18 cm) in soils cultivated for 7, 22 and 35 years (Table 4.3). This could be an indication of plough pan formation below a depth of 15 cm especially after 22 and 35 years of cultivation (Figure 4.7). However, in the grasslands and soils cultivated for 2 years, only PR in the surface soil layer was significantly lower than either of the soil depths.

Table 4.3. Penetration resistance in the acacia-based grassland (0) and cultivation durations of 2, 7, 22 and 35 years in Langano, Ethiopia.

	Penetration resistance (MPa) for varying cultivation durations					Tukey's HSD
Depth (cm)	**0**	**2**	**7**	**22**	**35**	(0.05)
0	0.72(0.11)	0.38(0.07)	0.40(0.10)	0.34(0.04)	0.20(0.02)	0.48
2	1.70(0.18)	0.56(0.07)	0.58(0.07)	0.48(0.08)	0.34(0.07)	0.63
4	1.78(0.19)	0.64(0.09)	0.62(0.07)	0.50(0.06)	0.44(0.06)	0.64
6	1.63(0.16)	0.72(0.10)	0.69(0.06)	0.67(0.05)	0.61(0.11)	0.60
8	1.48(0.13)	0.85(0.14)	0.77(0.07)	0.82(0.04)	0.83(0.10)	0.62
10	1.22(0.15)	0.96(0.11)	0.81(0.06)	0.91(0.05)	0.93(0.14)	0.64
12	1.18(0.16)	0.97(0.09)	0.92(0.09)	1.09(0.10)	0.96(0.14)	0.70
14	1.10(0.15)	0.99(0.07)	1.10(0.15)	1.28(0.05)	1.05(0.09)	0.66
16	1.24(0.18)	1.00(0.10)	1.20(0.16)	1.31(0.08)	1.29(0.11)	0.79
18	1.17(0.19)	1.05(0.06)	1.25(0.15)	1.33(0.11)	1.35(0.15)	0.82
Tukey's HSD (0.05)	0.89	0.53	0.58	0.47	0.60	

Mean differences greater than Tukey's HSD values down a column with depth and along a row with respect to cultivation durations, are significantly different (p = 0.05).

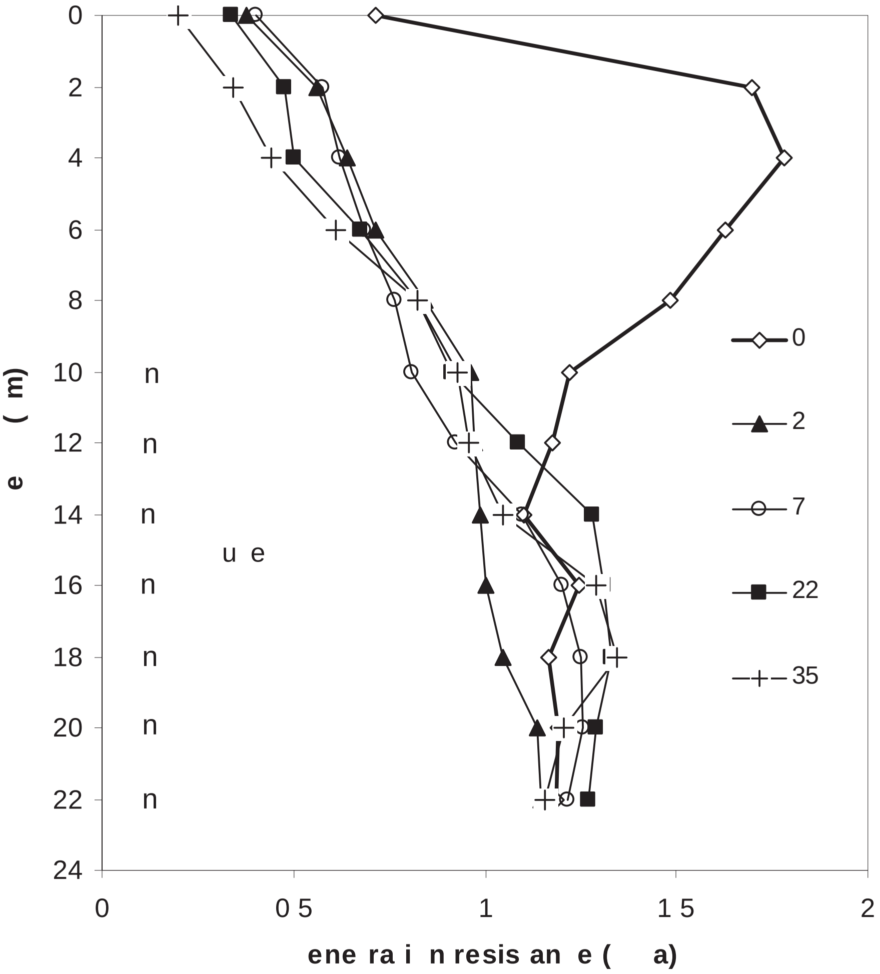

*Figure 4.7. Penetration resistance of the top 22 cm soil layer in the acacia-based grasslands (0), and cultivation durations of 2, 7, 22 and 35 years in Langano, Ethiopia. Mean separations were made based on the Tukey's HSD test. *Significant at α = 0.05 level of probability, ** Significant at α = 0.001 level of probability, and ^{ns} not significantly different.*

4.4 Discussion

The lack of significant differences in organic carbon and soil bulk density amongst the various cultivation durations since land use conversion (Table 4.1) is not in line with Limenih et al. (2005) who found significant differences in organic carbon stock and bulk density in surface soils cultivated for different durations. However, their comparison was conducted in an area of the Ethiopian Rift Valley with a very different native vegetation pattern and inherent soil properties. On the other hand, Nyssen et al. (2008) revealed, due to the overgrazed nature of the grasslands, no significant differences in the soil organic carbon between the cultivated lands and grazing land in the CRV. Other findings in other parts of the world also revealed that soil carbon stock in grazing lands depend on grassland management (Conant et al., 2001; Post and Kwon, 2000). Furthermore, in the younger soils of the lower elevation areas of the CRV where this study was done (Verheye, 1978), there were indications of carbon additions from the carbon-rich limnic sediments and that the build-up of the stock did not start from zero (Nyssen et al., 2008). Although further studies are required to quantify the annual additions, the free roaming animals on the cultivated lands following crop harvest might be important sources of organic matter input in the form of fresh manure. Livestock-mediated nutrient transfer from grazing lands to cultivated fields around homesteads has been revealed from mixed-farming systems of western African drylands by Powell et al. (2004) and Hierenaux et al. (1997).

The significant increase in infiltration rate soon after the start of cultivating acacia-based grassland is most likely due to the tillage, which improves the porosity of the compacted surface soils in the acacia-based grasslands as a result of long-term trampling by animals. However, with an increase in the years of cultivation, the infiltration rate showed a weak declining trend, possibly attributable to the susceptibility of the sandy loam soils to crusting and sealing, which could also be accentuated by continuous manipulations by the traditional *Maresha* ploughing. The effect of surface crusts in reducing infiltration and enhancing surface runoff has been reported earlier by Rockström et al. (1998), and Hoogmoed and Stroosnijder (1984). The relative increase, albeit smaller, in the penetration resistance of the soils immediately below the plough layer under long cultivation durations (Figure 4.7; Table 4.3) could also explain the decline in infiltration rate in the subsurface soils. The variation in penetration resistance might not be fully explained by the variation in bulk density and soil water content (Dexter et al., 2007). The effect of long-term *Maresha* ploughing on the development of plough pans has also been previously implied by Temesgen et al. (2009) and Aune et al. (2001). Regarding the change in infiltration rate over time for a single infiltration event, the more gradual decrease in infiltration rate of the surface soils in the acacia-based grassland compared to the cultivated soils suggests that the acacia-based grassland may be less sensitive to ponding than the cultivated fields and will have increased cumulative infiltration from long duration rains.

The low rate of soil evaporation in the acacia-based grassland compared to the cultivated plots could be due to the shading effect of the acacia trees, albeit sparse, and the modified microclimate on the acacia-based grasslands. On the other hand, the significant increase in cumulative evaporation with the increase in the years of cultivation could be explained by the associated increase in the surface (0-5cm) soil water content following a rain event that satisfied field capacity of the soils (Table 4.2). Long-term tillage in the tropics could cause structural deterioration and enhance soil crusting in sandy loam soils that in turn impede infiltration (Hoogmoed, 1999; Stroosnijder and Hoogmoed, 1984) and hence could cause surface water stagnation immediately after rain events. The lower wetting zone immediately after rain events in crusting soils could cause higher evaporation (Bresler and Kemper, 1970). Higher rates of stage one evaporation were also observed from conventional tillage than from no-till treatments (Steiner, 1989). The strong correlation ($R^2 = 0.83$) between the slope of cumulative evaporation and cultivation duration implies that the rate of cumulative evaporation increases inevitably with long-term cultivation. It is, therefore, likely that based on the current land management scenarios, long-term cultivation characterised by continuous maize mono-cropping and repeated tillage each season by *Maresha* ploughing would accentuate loss of soil water by evaporation from the sandy loams of the CRV. By inference, the maize crops growing on long-term tilled soils would suffer more from dry-spells (consecutive days without effective precipitation) which are common in the CRV during the Ethiopian rainy season (Segele and Lamb, 2005).

Based on a review of the historical developments of *Maresha* tillage, Gebregziabher et al. (2006) suggested the possibility of improving animal traction tillage implements through use of recent developments in farm technologies and mathematical modelling techniques supported by computer-based simulations, as well as new methodologies in research. Less inversion tillage techniques modified from the traditional *Maresha* tillage revealed better crop and water productivity values (Temesgen, 2007). Contemporary research efforts for developing appropriate tillage techniques (Mrabet, 2002; Temesgen, 2009) indicate the possibility of sustaining rainfed agriculture in drylands thereby improving the rainwater use efficiency (Stroosnijder, 2009). Therefore, concerted effort is required to adapt and develop the indigenous tillage systems in line with the principles of conservation agriculture appropriate to drylands (Rockström et al., 2009; Wall, 2007). Organic amendments such as mulching and manure additions were found very important in improving soil structure and enhancing infiltration of crusting sandy loam soils (Pikul and Zuzel, 1999; Or and Ghezzhei, 2002; Gicheru et al., 2004; Zeleke et al., 2004). Manure is not used for heating in the CRV since there is still enough firewood available. Hence, there is ample opportunity to promote soil management through manure additions in the CRV. Incorporation of agroforestry trees such as *Faidherbia albida* enhances crop production in drylands through soil improvements (Kho et al., 2001) while exploiting the water from depth in the soil (Roupsard et al., 1999). In light of this, it appears that there are ways to increase the rainwater use efficiency and sustainably develop the smallholder-based agriculture through improved tillage and soil management in the predominantly rainfed maize farming system of the CRV.

4.5 Conclusions

The acacia-based grasslands of the Central Rift Valley drylands in Ethiopia are being steadily converted to cultivated land in response to the burgeoning population. Based on our study of soil physical properties in response to land use conversion and long-term cultivation using the traditional *Maresha* plough, the following conclusions are drawn.

1) In the present mixed-farming system, conversion of acacia-based grassland into cultivated land did not significantly reduce the organic carbon content of the soils.
2) The infiltration rate of the surface of the sandy loam soils increased soon after converting to cultivation due to the loosening of the compacted topsoil. However, thereafter, a weak decreasing trend in the infiltration rate seemed to occur with increasing years of cultivation.
3) Soil evaporation, following rain events that satisfied field capacity of the soils, increased significantly following land use conversion and long-term tillage thus increasing the sensitivity of the soils to dry-spells and droughts.
4) Although the penetration resistance of the surface soils (0-8cm) was higher in the grassland than in the cultivated plots, plots that had been cultivated for a longer period of time (22 and 35 years) showed development of a plough pan immediately below the plough layer.
5) Further studies are needed to explain the correlation between long-term *Maresha* cultivation and soil structural changes such as soil aggregate stability and surface crusting in the drought-prone sandy loam soils of the CRV.

The long-term effects of continuous *Maresha* cultivation being a significant increase in soil evaporation and tendency toward decreased infiltration served as evidence of the need for the development of improved tillage techniques and concurrent development of appropriate soil management practices that could improve the soil water retention capacity. Maximization of rainwater use efficiency, through improved tillage and appropriate soil management, is an apt strategy to improve and sustain the smallholder-based rainfed agriculture in the drought-prone CRV of Ethiopia.

Chapter 5

To tie or not to tie ridges for water conservation in the Rift Valley drylands of Ethiopia

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To tie or not to tie ridges for water conservation in Rift Valley drylands of Ethiopia

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Abstract

The Rift Valley drylands of Ethiopia are characterized by poor, sandy loam soils and unreliable rainfall conditions. The aim of this study was to examine the potential benefit of rainwater harvesting by tied-ridges and improved soil fertility on maize productivity through field experimentation and simulation with the FAO's AquaCrop model. The effect of tied-ridges with and without manure on maize yield at smallholder farms was studied during the years 2009 (very dry, 96% probability of exceedance) and 2010 (normal year, 46% probability of exceedance). Tied-ridges in combination with manure increased grain yield by 47% while tied-ridges in isolations increased the yield by 26% compared to traditional tillage without manure in the normal year. Long-term simulations with the FAO's AquaCrop showed that the root zone soil water may exceed field capacity for consecutive days during above average rainfall seasons in the shallow sandy loams. The question thus is when to tie or not to tie ridges. The effect of tied-ridges and improved soil fertility was examined in response to different amounts of seasonal rainfall, number of rainfall days and sowing months. Simulations revealed that, during below average rainfall seasons (280-330 mm), tied-ridges are more effective at improving crop yields than enhancing the fertility level of the soil. But during above average rainfall seasons, the rainwater that is held in tied-ridges can be more effectively utilised when the current fertility level of the soil is improved. Compared to traditional tillage without fertilizer, tied-ridges in combination with optimal fertiliser application (96% soil fertility level) may increase transpiration by 6 - 43% depending on the rainfall pattern. Hence, the rainwater use efficiency of maize can be doubled. It is, therefore, concluded that combined use of tied-ridges and farmyard manure can enhance maize yield under wide range of rainfall conditions. The Maresha-modified ridger used in this study can be popularized among Ethiopian farmers due to its simplicity and effectiveness.

5.1 Introduction

Out of the 13.6 million hectares of cultivated land in Ethiopia, close to 97% is rainfed implying that the nation's annual harvests depend heavily on the patterns of the seasonal rains (Awulachew et al., 2005; FAO, 2005). Given that Ethiopia's national GDP is mainly based on agriculture, the annual GDP growth during 1983-2000 showed strong correlation with rainfall variation (WWAP, 2009). Seasonal rainfalls are highly unpredictable and variable in Ethiopia (Gissila et al*.,* 2004) contributing to higher risk of production in arid and semi-arid regions due to less crop water availability during the growing seasons (Tesfaye and Walker, 2004). Hence, smallholder-based agricultural production varies noticeably from year-to-year (Tesfaye and Walker, 2004).

Maize (*Zea mays L.)* is critical to smallholder livelihoods in Ethiopia and has the largest smallholder coverage at 8 million holders, compared to 5.8 million for teff (*Eragratis teff*) and 4.2 million for wheat (CSA, 2010; IFPRI, 2011). It is also the largest crop nationwide by volume at 3.9 million tons (2.2 Mg ha^{-1} on average) in 2009/10, compared to teff at 3.1 million tons (1.2 Mg ha^{-1}) and wheat at 3.0 million tons (1.8 Mg ha^{-1}) (CSA, 2010). Maize is the staple food particularly in dryland regions while teff is more important in highland regions. Maize production in Ethiopia is significantly limited due to low soil fertility and agricultural water scarcity during critical growth stages (Debelle et al., 2001; Demeke et al., 1997; Senay et al., 2003).

The arid, semi-arid and dry sub-humid parts of Ethiopia cover about 65% (close to 700,000 km^2) of the total land mass of the country (EPA, 1998), and 46% of the total arable land (Yonas, 2001). The Ethiopian Rift Valley, which covers the major portion of the vast dryland areas, is undergoing increasing land-use conversion from pastoral to mixed crop-livestock systems (Biazin and Sterk, 2011; Dessie and Kleman, 2006; Garedew et al., 2009; Tsegaye et al., 2010). Not only the year to year rainfall variability (Tilahun, 2006), but also the non-productive loss of rainfall through soil evaporation and surface runoff limit rainfed agriculture. Up to 40% of the seasonal rainfall may be lost in the form of surface runoff in the Rift Valley drylands of Ethiopia (Welderufael et al*.,* 2008).

Ridging, which creates furrows by opening the soil in between, is widely applied in different areas (Jones and Stewart, 1990; Lal, 1990; Lal, 1991). In the teff production areas of the Tigray region of Ethiopia, farmers traditionally make contour ridges, locally called *terwah*, at 2-4 m wide intervals to trap water for later crop use (Gebreegziabher et al., 2009). In the central Rift Valley areas of Ethiopia, the traditional *shilshalo* ridging practice is done 3-4 weeks after planting of maize as a means of breaking the surface crusts and enhancing infiltration (Biazin et al., 2011a). In areas of low and erratic rainfall, the furrows created by ridging can be left open, or closed at regular intervals for holding water and facilitating infiltration. To close furrows, they are blocked with earth ties between the ridges; hence the common name for this water conservation system is 'tied-ridges' or furrow diking. In tied-ridges, the earth ties spaced at fixed distances form a series of micro-catchment basins in the field (Lal, 1990; Nyamudeza and Jones, 1994; Wiyo et al., 1999). The significant role of tied-ridges in improving water and crop productivity in arid and semi-arid regions has been reported (Araya and Stroosnijder, 2010; Biamah et al., 1993; Jensen et al*.,* 2003; McHugh et al., 2007; Motsi et al., 2004). However, depending on the pattern of the seasonal rainfall, tied-ridges may also cause waterlogging which can negatively affect crop yields (Jensen et al*.,* 2003; Olufayo et al., 1994). The question thus is when to tie or not to tie ridges in response to different patterns of rainfall in the Rift Valley drylands of Ethiopia.

Given the poor soil fertility level of the Rift Valley drylands in Ethiopia (Biazin et al., 2011b; Itanna, 2005), a single intervention through rainwater harvesting techniques may not bring about substantial impact on crop productivity. Studies in arid and semi-arid regions of sub-Saharan Africa revealed that single interventions through water conservation could improve crop yields by up to 50% (Araya and Stroosnijder, 2010; Hensley et al*.,* 2000; Walker et al*.,* 2005) while the combined use of tied-ridges and nutrient inputs has resulted in twofold to sixfold crop yields as compared to traditional farming practices without fertiliser use (Jensen et al*.,* 2003; Zougmoré et al., 2003). Other studies have shown that soil improvements through the use of farmyard manure and composting combined with in situ rainwater harvesting techniques has been beneficial for rainfed agricultural systems in arid and semi-arid regions (Fatondij et al., 2006; Gicheru et al., 2004; Reij et al., 2009; WOCAT, 2007). In the Rift Valley drylands of Ethiopia, there is ample opportunity to use animal manure for soil fertility improvements.

Simulations can be a substitute for expensive and long-term field studies to evaluate effects of tied-ridging in response to different seasonal rainfall patterns and fertility levels. Krishna (1989) tried to simulate the effect of conserving runoff by furrow diking on crop yields in Texas, USA. However, his deterministic models require detailed crop and soil data inputs. Wiyo et al. (1999) used a simple field capacity-based water balance model (TIEWBM) to simulate the effect of tied-ridges on water balance components under different soils and rainfall regimes in Malawi. However, the effect of tied-ridges on crop yields in response to various soil fertility levels could not be simulated. Relative to other simulation models, the FAO's AquaCrop model requires a smaller number of parameters and input data to simulate the yield response to water for most of the major field crops cultivated worldwide (Steduto et al*.,* 2009). Therefore, Aqua Crop was used in this study to conduct long-term simulations of the effect of tied-ridges in response to different amounts of seasonal rainfall, sowing time and fertility levels. The outcome of the long-term simulation can be used to understand the scenario of combining tied-ridges and soil fertility improvements in response to different amounts of seasonal rainfall and time of sowing.

5.2 Materials and Methods

5.2.1 Site characteristics and measured data

The field experiment site is located in the Central Rift Valley (CRV) of Ethiopia around Langano ($38^0$40 E, $7^0$33 N), which is situated about 190 km south of the capital, Addis Ababa. It lies at about 1600 meter above sea level and has a slope of 2-3%. With an aridity index of 0.37 (P/ET_o^{-1}), the study area is a semi-arid dryland according to the UNCCD classification of drylands (UNCCD, 2000; MEA, 2005). The annual rainfall varies between 270 and 960 mm (CV = 30%) with a mean of 650 mm for the past 30 years. Although the area was previously covered by dense acacia woodlands, which had been used by pastoral Oromo people coming from the nearby highland areas, a significant proportion of the area has become subjected to cultivation and grazing over the last five decades (Biazin and Sterk, 2011; Eshete, 1999). Major crops are maize (*Zea mays* L.) and haricot bean (*Phaseolus vulgaris* L.). Livestock consists mainly of goats and cattle. Following crop harvests, livestock freely graze on the crop residues. Although cattle manure is abundant around homesteads where households corral their livestock, most of the local households do not put any manure on the cultivated fields.

The geological and geomorphologic features of the region are the result of volcano-tectonic and sedimentation processes (Ayenew, 2007). The volcanic products were derived from tuff, ignimbrite and volcanic ash. The soil is classified as Haplic solonetz with a texture ranging from loamy sand to sandy loam (Biazin et al., 2011b; Itanna, 2005). The soil is poor in fertility and shallow with an impermeable calcite layer between 0.55 and 0.70 m. It readily compacts and is liable to crusting and drought. The measured soil water properties are presented in Table 5.1.

Table 5.1. Soil physical properties[1] of experimental fields near Langano, Central Rift Valley, Ethiopia.

Soil layer (m)	Soil water content (Vol %)			BD	K_{sat}
	Sat	FC	PWP	(g cm^{-3})	(mm d^{-1})
0.00-0.15	41	20	10	1.12	280
0.16-0.30	41	21	9	1.16	230
0.31-0.45	42	21	8	1.18	110
0.46-0.60	40	20	9	1.21	50

[1] *Sat, water content at saturation; FC, field capacity; PWP, permanent wilting point; BD, bulk density;* K_{sat}, *saturated hydraulic conductivity*

During the 2009 and 2010 growing seasons, field experimentation was undertaken to examine the potential benefit of rainwater harvesting using tied-ridges in combination with application of farmyard manure. Split-plot designs were used. The tied-ridges and the traditional tillage were considered as the main plots and presence or absence of farmyard manure as the sub-plots. Main plot areas were 30 x 15 m and sub-plots were 15 x 15 m. The treatments were replicated in four volunteer farmers' fields thereby making a total of 16 test plots. Farmyard manure was added to the plots at the rate of 4.5 Mg ha^{-1} before planting and incoporated into the soil during the primary and secondary tillages. At the time of application, the farmyard manure had 1.4% nitrogen and 2.1% organic carbon.

Unlike previous experiences of tying the ridges manually (Araya and Stroosnijder, 2010; McHugh et al., 2007; Nyssen et al., 2011), the Maresha-modified ridger (Temesgen, 2007) was used in this study. This type of ridger makes ridges with 26 cm wide furrows while the traditional *Dirdaro* tillage had a furrow width of only 20 cm. Both the tied-ridges and the traditional *Dirdaro* tillage systems had a similar furrow depth of 16 cm. The new ridger makes the tied-ridges easily by raising the ridger at constant intervals of 4 m by the plow-man. This reduces extra cost of labour in manual tying of ridges. Both the tied-ridges and the traditional *Dirdaro* were made after every two planting rows making an average spacing of 55 cm between consecutive ridges (Figure 5.1).


(a) (b)

Figure 5.1. (a) Tied-ridges prepared using the Maresha-modified ridger and (b) furrows made with the traditional Dirdaro tillage system, both practiced during sowing in the CRV, Ethiopia. Pictures were taken 7 days after sowing of maize and one day after a rain event (Photo by Birhanu Biazin, May 2010).

Meteorological observations were made over the entire experimental period of 2009 and 2010 using an automatic weather station (Eijkelkamp Equipment, Model 16:99 Giesbeek, the Netherlands). Therefore, reference evapo-transpiration was determined using the FAO Penman-Monteith equation as described in Allen et al. (1998) by the ET_o calculator (FAO, 2009a). Daily precipitation was also measured using a conventional rain gauge installed near the experimental plots. The year 2009 was a very drought year (96% probability of rainfall exceedance) while 2010 had a normal growing season (46% probability of rainfall exceedance). The daily rainfall and ET_o during the two growing seasons is depicted in Figure 5.2.

Soil water content profiles were measured twice a week with a Time Domain Reflectometer (TDR) (Eijkelkamp Equipment, Model 14.62, Giesbeek, the Netherlands) depth probe from 16 access tubes installed in the plots. Additionally, gravimetric water content was determined intermittently based on soil samples collected during the growing season. The gravimetric values were converted to volumetric values by multiplying with the bulk density of the soil samples. The result was regressed with that of the TDR observations. Conversion of the TDR readings to the standard soil water content method was possible using Equation 5.1 having a coefficient of determination ($R^2 = 0.71$, N=18). The difference between the TDR readings and the standard gravimetric method is somehow high may be due to the difference in soil types in the study area and that used for calibration of the TDR from the company.

$$\text{Soil water content (Vol \%)} = 1.29 \times \text{TDR reading (Vol \%)} \qquad [5.1]$$

For surface runoff determination, each of the main test plots were delineated as hydrologically isolated plots. Plastic barrels were inserted halfway and at the bottom end of the experimental plots to collect runoff. The barrels were emptied after every rainy day that produces runoff. The measured volume of runoff was converted into units of mm. During the 2009 growing season, surface runoff was observed only for three days in July: 7, 14 and 20. However, during the 2010 growing season, the runoff was observed continuously from sowing to harvest.

A local maize cultivar (*Awassa BH540*) was planted with a density of 40,000 plants ha^{-1}. Plant parameters such as canopy cover, rooting depth and yield were monitored. Canopy cover (CC) was estimated regularly by visual inspection at clear skies around noon (11:00 AM-2:00 PM local time) when shadows are clearly seen on the ground. Graduated sticks and rulers of 3 m were placed on the ground to estimate the percent of the soil surface covered by the maize canopy. A similar technique has been used elsewhere (Mhizha, 2010; Nyakatawa et al., 2000). Maximum rooting depth was estimated by visual inspection after digging profile pits when the maximum canopy cover was achieved and at around maturity of the maize plant. Final aboveground biomass and grain yields were estimated for each treatment by air drying of crop samples after harvest.

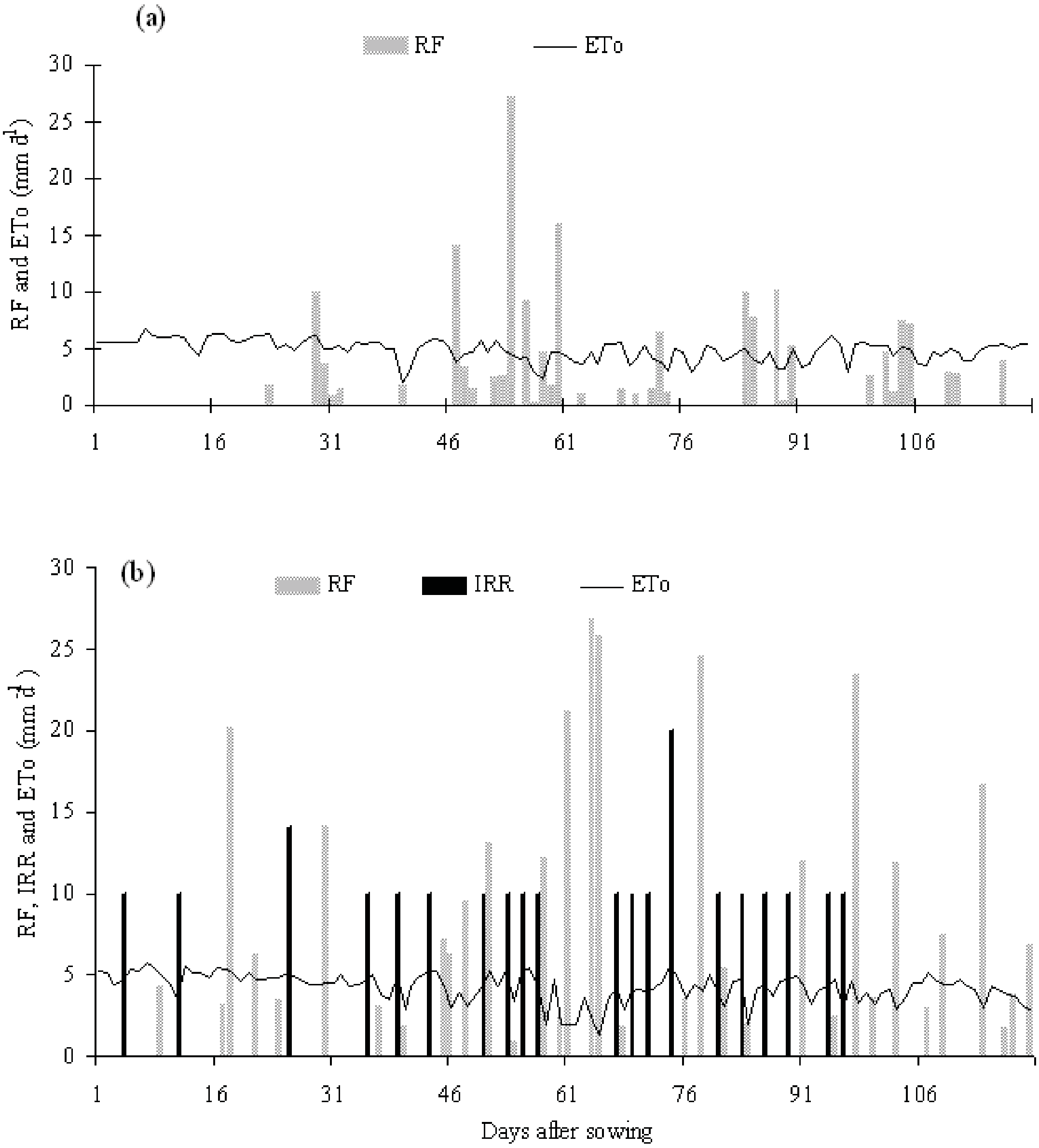

Figure 5.2. Daily rainfall (RF), reference evapo-transpiration (ET_o) and applied irrigation (IRR, see section 5.2.2.2) at the experimental field during the cropping seasons in 2009 (a) and 2010 (b) Langano, Ethiopia.

5.2.2 Description of AquaCrop and test of transferability

5.2.2.1 Model description and data inputs

The FAO's AquaCrop model was developed to simulate attainable yield in response to water, with much efforts underpinning the effects of water stress on crop yields (Hsiao et al., 2009; Raes et al., 2009; Steduto et al., 2009). Evolving from a previous approach by Doorenbos and Kassam (1979) where relative Evapotranspiration (ET) is pivotal in estimating yield, AquaCrop uses only the productive transpiration (Tr) and a normalized water productivity (WP*, biomass per unit of cumulative transpiration) to estimate the total biomass (Steduto et al., 2009; Equation 5.2). By appropriately normalizing the crop water productivity for different crops under different climatic conditions, the model uses WP* as a conservative parameter (Steduto et al., 2007). The harvestable yield (Y) is expressed as a function of biomass (B) using a harvest index (HI) and distinguishes between environmental stress effects on B from those on HI (Equation 5.3). AcquaCrop is progressed by developing a simple canopy growth and senescence model as the basis for the estimate of Tr and its separation from evaporation (E) (Raes et al., 2009; Steduto et al., 2009).

$$B = WP^* \times \Sigma Tr \qquad [5.2]$$

Where:
Tr is crop transpiration (in mm) and
WP* is water productivity parameter in units of kg (biomass) m^{-2} (land area) mm^{-1} (mm of cumulated water transpired over the time period in which the biomass is produced).

$$Y = B \times HI \qquad [5.3]$$

AquaCrop organizes its soil–crop–atmosphere continuum by including (i) the soil, with its water balance; (ii) the plant, with its growth, development, and yield processes; and (iii) the atmosphere, with its thermal regime, rainfall, evaporative demand, and carbon dioxide concentration (Hsiao et al., 2009; Raes et al., 2009; Steduto et al., 2009). Additionally, the levels of soil fertility and irrigation are considered as management aspects as they affect crop development, water productivity, and crop adjustments to stresses, and thus final yield. Hence, AquaCrop uses inputs from five files for simulation: Climate, Crop, Soil, Management, and Initial soil water status. The different user-specific and conservative input parameters used for this study are described herein.

The climate file is user-specific and consists of three sub-files: (i) minimum and maximum air temperature, (ii) reference evapotranspiration (ET_o), and (iii) rainfall, all daily values. Furthermore, the CO_2 concentration uses the default value of Mauna Loa Observatory records in Hawaii (Steduto et al., 2009). Daily rainfall, minimum and maximum temperature values were collected for the years between 1981 and 2006 from the Ethiopian Meteorological Organization, Langano station. Because, daily values of solar radiation, relative humidity and wind speed were missing in the long-term data, the reference evapotranspiration was estimated based on the Hargreaves equation (Equation 5.4) after calibration using the procedure in the FAO *Irrigation and Drainage Paper* 56 (Allen et al., 1998).

$$ET_H = 0.0023(T_{mean} + 17.8)\ (T_{max} - T_{min})^{0.5}R_a \qquad [5.4]$$

Where:
ET_H is the evapotranspiration (mm day^{-1}) based on the Hargreaves equation,
T_{min} is the daily minimum temperature (^oc),
T_{max} is the daily maximum temperature (^0c),
T_{mean} is the mean daily temperature (the sum of T_{max} and T_{min} divided by two), and
R_a is daily extra-terrestrial radiation (mm day^{-1}) that was determined for the geographic location using the procedure by the FAO *Irrigation and Drainage Paper* 56 (Allen et al., 1998).

The Hargreaves equation was calibrated with the FAO Penman-Monteith equation using data collected from the automatic weather station during 2009 and 2010 (N = 160, R^2 = 0.86) and the empirical coefficients were determined (Equation 5.5).

$$ET_o = 1.059\ ET_H - 0.103 \qquad [5.5]$$

The crop input file encompasses both conservative and user-specific parameters, some of the latter being cultivar-specific. The model has been parameterized and tested for maize based on six seasons at the University of California, Davis (Hsiao et al., 2009) and validated for both irrigated and water deficient field maize based on data from different climatic zones around the world (Heng et al*.,* 2009). Hence, the widely applicable conservative parameters were used for this study (Table 5.2). The user-specific parameters for the local maize variety (*Awassa BH540*) were determined from non-stressed (fully irrigated and well-fertilized) maize during the 2010 experimental season in the study area (Table 5.3).

The management files include irrigation and field management options. The irrigation file was used only for the calibration of soil fertility level as described in section 5.2.2.2. The field management menu includes also surface characteristics such as runoff. Runoff was described with a curve number (CN) value of 88 (USDA, 1964) and was assumed zero when the tied-ridges were considered for the simulation (see section 5.2.3). The soil input parameters described in Table 5.1 were used for all simulations.

Initial soil water content was determined based on onset of the historical simulations. Hence, the onset of the rainy season which is assumed to be a successful planting date for maize in the central Rift Valley was generated from AquaCrop as defined by the rainfall accumulated in five consecutive days with at least 30 mm (Biazin and Sterk, 2011). Hence, one or more onset/s could be identified during March 1 - June 30 for each year of simulation. Based on the experience of the field measurements immediately after onset during 2009 and 2010, the initial soil water content was fixed at 75% of soil water content at field capacity. Geerts et al. (2010) used a similar technique of setting the initial soil water content of the rooting zone for long-term simulation with AquaCrop.

Table 5.2. Crop (conservative) input parameters of AquaCrop for maize.

Description	Value	Unit/ meaning
Base temperature	8	^{0}C
Cut-off temperature	30	^{0}C
Canopy cover per seedling at 90% emergence	6.5	cm^2
Canopy growth coefficient (CGC)	1.3	Increase in CC relative to existing CC (% GDD^{-1})
Crop coefficient for transpiration at CC = 100%	1.03	full canopy transpiration relative to ET_o
Decline in crop coefficient after reaching maximum canopy cover (CC_x)	0.3	%, Decline per day due to leaf aging
Canopy decline coefficient (CDC) at senescence	1.06	%, decrease in CC relative to CC_x per GDD
Leaf growth threshold p—upper	0.14	As a fraction of TAW, above this leaf growth is inhibited
Leaf growth threshold p—lower	0.72	Leaf growth stops completely at this point
Leaf growth stress coefficient curve shape	2.9	Moderately convex curve
Stomatal conductance threshold p—upper	0.69	above this stomata begin to close
Stomatal stress coefficient curve shape	6.0	highly convex curve
Senescence stress coefficient p—upper	0.69	Above this stomata begins to close
Senescence stress coefficient curve shape	2.7	Moderately convex curve
Vol % at anaerobic point (with reference to saturation)	6	%, Moderately tolerant to water logging
Reference harvest index	48	%
Coefficient, inhibition of leaf growth on HI	7	HI increased by inhibition of leaf growth at anthesis
Coefficient, inhibition of stomata on HI	3	HI reduced by inhibition of stomata at anthesis

Table 5.3. Phenological observations and related crop parameters of local maize (*Awassa BH540*) used as user-specific inputs for AquaCrop.

Description	Value	Unit/ meaning
Time from sowing to emergence	7	Calendar days
Time from sowing to maximum canopy cover	65	Calendar days
Time from sowing to flowering	60	Calendar days
Duration of flowering	15	Calendar days
Time from sowing to start of senescence	95	Calendar days
Time from sowing to harvest	120	Calendar days
Maximum rooting depth	0.6	Meter
Maximum canopy cover (CC_x)	83	%, function of plant density (40,000 plants ha^{-1})
Soil fertility stress coefficient for canopy expansion (Ksexp)	17	%
Soil fertility stress coefficient for the maximum canopy cover ($KsCC_x$)	27	%
Soil fertility stress coefficient for water productivity (KsWP)	47	%
Average daily decline of the canopy cover once maximum canopy cover is reached (fCDecline)	0.59	% day^{-1}, percentage of decline per day

5.2.2.2 Model calibration and validation

FAO's AquaCrop model was parameterised for maize (Hsiao et al*.,* 2009) and validated for wider applicability around the world under both irrigated and water deficient field maize (Heng et al., 2009). Hence, in this study, only the transferability of the conservative parameters (Heng et al., 2009; Hsiao et al*.,* 2009) was tested for a local maize variety (*Awassa BH540*) after calibrating the fertility level of the soil. The calibration of soil fertility followed the procedure by FAO (2009b). During the 2010 growing season, experimental plots (6 x 3 meter) were set in the field with three replications. Based on previous recommendations of fertilizer applications on maize fields around the study area (Debele et al*.,* 2001; Demeke et al*.,* 1998), 100 kg ha^{-1} Urea in two applications and 100 kg ha^{-1} of DAP were applied on the reference fields and nothing was applied on the calibration fields. Farmyard manure (4.5 Mg ha^{-1}) was applied on the reference fields to keep the fertility level of the soil at optimum conditions continuously throughout the growing season. Water was applied regularly to keep the soil water content near field capacity in both the reference and calibration fields (Figure 5.2).

Canopy development and other phenological observations were made from the reference fields during the growing season (Table 5.3). The biomass harvested at the end of the crop cycle from the calibration field expressed as a percentage of the biomass from the reference field was considered as an expression of the soil fertility level. Heng et al. (2009) and Hsiao et al. (2009) used a normalised water productivity (WP*) value of 33.7 g m^{-2} for calibration and validation of either irrigated or water-stressed maize under optimal soil fertility conditions. However, in the maize belt of Zimbabwe, a better simulation was achieved for an early maturing (140 days) maize when a WP* value of 29 g m^{-2} was used (Mhizha, 2010). Given an early-maturing (120 days) cultivar, a shallow rooting depth of 0.6 m and a low plant density (40,000 plants ha^{-1}), a better simulation was achieved by trial and error when the WP* was adjusted to 30.7 g m^{-2}.

To evaluate the performance of the model and transferability of the conservative parameters for maize, validation was done based on rainfed fields during 2010 with tied-ridges and the traditional tillage systems. The 2009 experimental season was unfortunately a very drought season (96% probability of rainfall exceeding) and hence, could not be used for validation of the model. Simulation for the tied-ridges was done by switching off the runoff as recommended by Raes et al. (2009). The root zone soil water content, canopy development, total biomass and grain yield were simulated and compared with the measured data. To test the goodness of fit, percent deviation (d), Root Mean Square Error (RMSE), and a linear regression coefficient (R^2) between observed and simulated data were made for biomass and grain yields. These values were compared with the values of previous studies on maize by Heng et al (2009) and Hsiao et al. (2009).

5.2.3 Simulating the response of tied-ridges to long-term rainfall and fertiliser uses

After validation, the model was used to simulate the biomass and crop yield due to the application of tied-ridges with combination of different levels of soil fertility. Climate data of the years 1981-2010 was used for long-term simulations as explained in section 5.2.2.1. The effect of three important rainfall attributes (total rainfall during the maize growing season, number of rainfall days and time of sowing) on the biomass and grain yield responses of tied-ridges was simulated. Total rainfall during the growing season in this case refers to the rainfall received during 120 days, starting from the date of onset as simulated by the model till harvest. Heng et al. (2009) implied that the model could be less effective in simulating highly water-stressed maize. Therefore, those onsets followed by low rainfall amounts (< 280 mm, 90% probability of exceedance) during the following 120 days were excluded from the simulations. Field observations during 2009 and 2010 implied that surface runoff is triggered when a rainfall of at least 12 mm per day was recorded. Therefore, the number of rainfall days with 12 mm or more was counted for each growing period of the 28 years series of simulations. Given that there can be one or more sowing dates per season, one or more simulations were made for onsets between March and end of June for each of the simulated years.

Once the current fertility level of the soil was calibrated, the effect of improving the fertility level in response to different rainfall patterns could be simulated. The simulated biomass and grain yield values were, therefore, regressed against rainfall amount, number of rainfall days and different sowing dates at different levels of soil fertility. Accordingly, the simulated yield with or without tied-ridges and in combination with different levels of soil fertility could be explained according to different rainfall patterns.

5.3 Results

5.3.1 Validation and test of transferability

The ratio of the total above ground biomass from the calibration field to that from the reference field was 0.46 implying that the fertility stress of the soil in the study area is 54%. Observed differences in canopy development between the calibration and reference fields were used to calibrate the soil fertility stress (Ks) coefficients describing the hampered canopy development (Figure 5.3, Table 5.3). Therefore, the model simulated the canopy cover progression, the biomass and grain yield of the fully irrigated and fertilised plots fairly well (Figure 5.3, Table 5.4). There was also good agreement between the simulated and measured values of canopy cover progression (Figure 5.4) under rainfed maize with tied-ridges (RMSE = 3.2) and traditional tillage (RMSE = 3.1). The simulation of the root zone soil water status was also satisfactory under both treatments of tied-ridges and traditional tillage (Figure 5.5). With RMSE values of 8.6 for traditional tillage and 7.3 for tied-ridges, the model slightly underestimated the observed soil water. The simulated biomass and grain yields of maize agreed fairly well with that of the observed values under the conditions of stress (rainfed and non-fertilised) and non-stress (irrigated and fully fertilised) (Table 5.4). The percent deviation of the simulated values from the observed values ranged from 2 to 18% and the coefficient of determination was high (R^2 = 0.98).

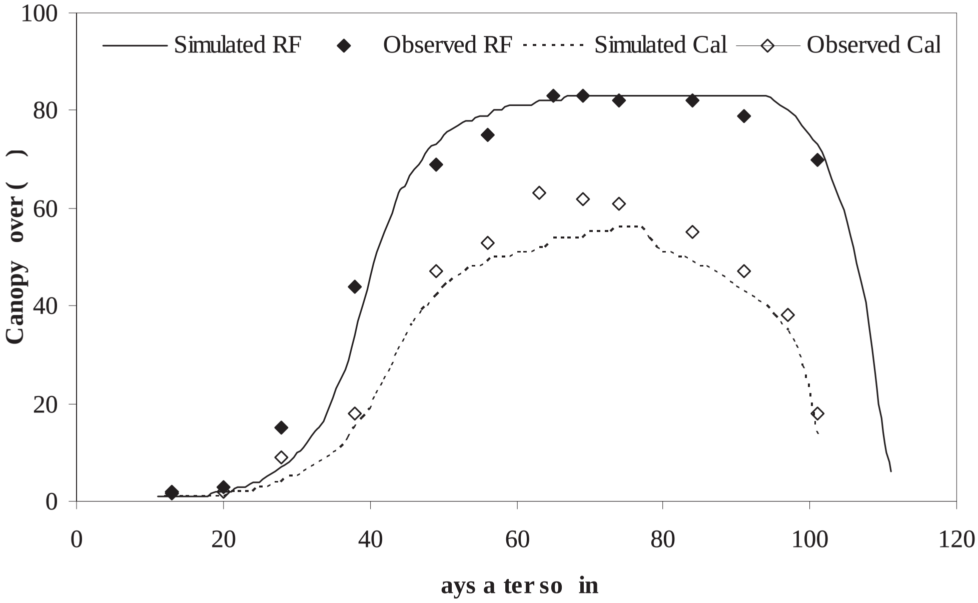

Figure 5.3. Simulated and observed maize canopy cover progression under a non-stressed fully irrigated and fertilised reference fields (RF) and non-fertilised but fully irrigated calibration fields (Cal) during 2010 in Langano, Ethiopia.

Table 5.4. Simulated and measured values of aboveground biomass and grain yield of maize in response to different treatments in Langano, Ethiopia.

Treatment	Final Biomass			Grain yield		
	Measured (Mg ha^{-1})	Simulated (Mg ha^{-1})	Deviation[‡] (%)	Measured (Mg ha^{-1})	Simulated (Mg ha^{-1})	Deviation (%)
Reference field	18.9	19.3	+1.5%	8.4	9.2	+9.5%
Calibration field	8.7	9.6	+10.3%	3.9	4.0	+2.6%
Rain fed field with tied-ridges	7.9	9.3	+17.7%	3.4	3.8	+11.8%
Rain fed field with traditional tillage	6.5	7.4	+13.8%	2.7	3.0	+11.1%

[‡] *Deviation (%) = (Simulated – measured) × 100/measured.*

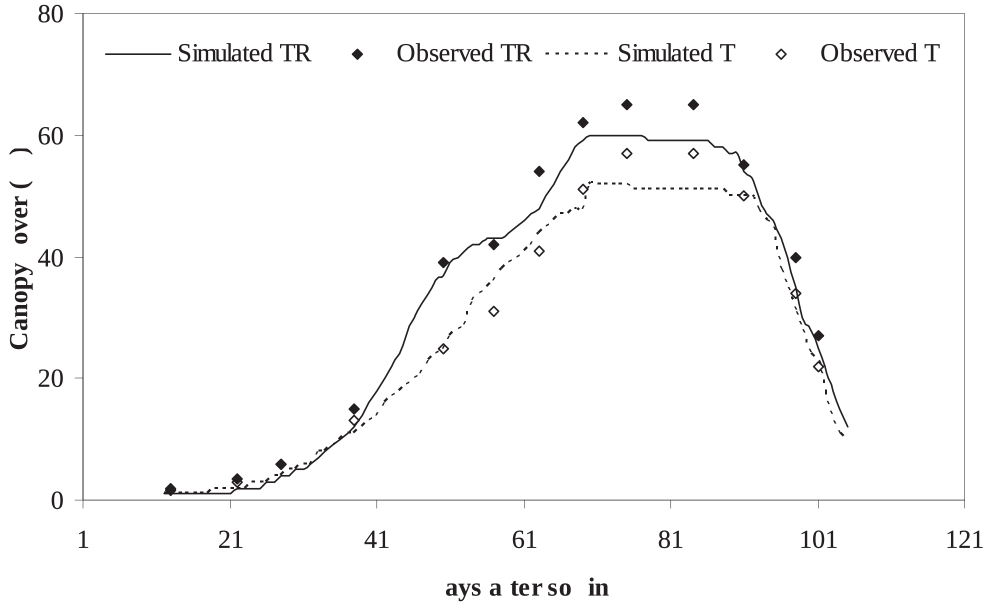

Figure 5.4. Simulated and observed maize canopy cover progressions based on rainfed cropping with tied-ridges (TR) and traditional tillage (T) without fertilizer during 2010 in Langano, Ethiopia.

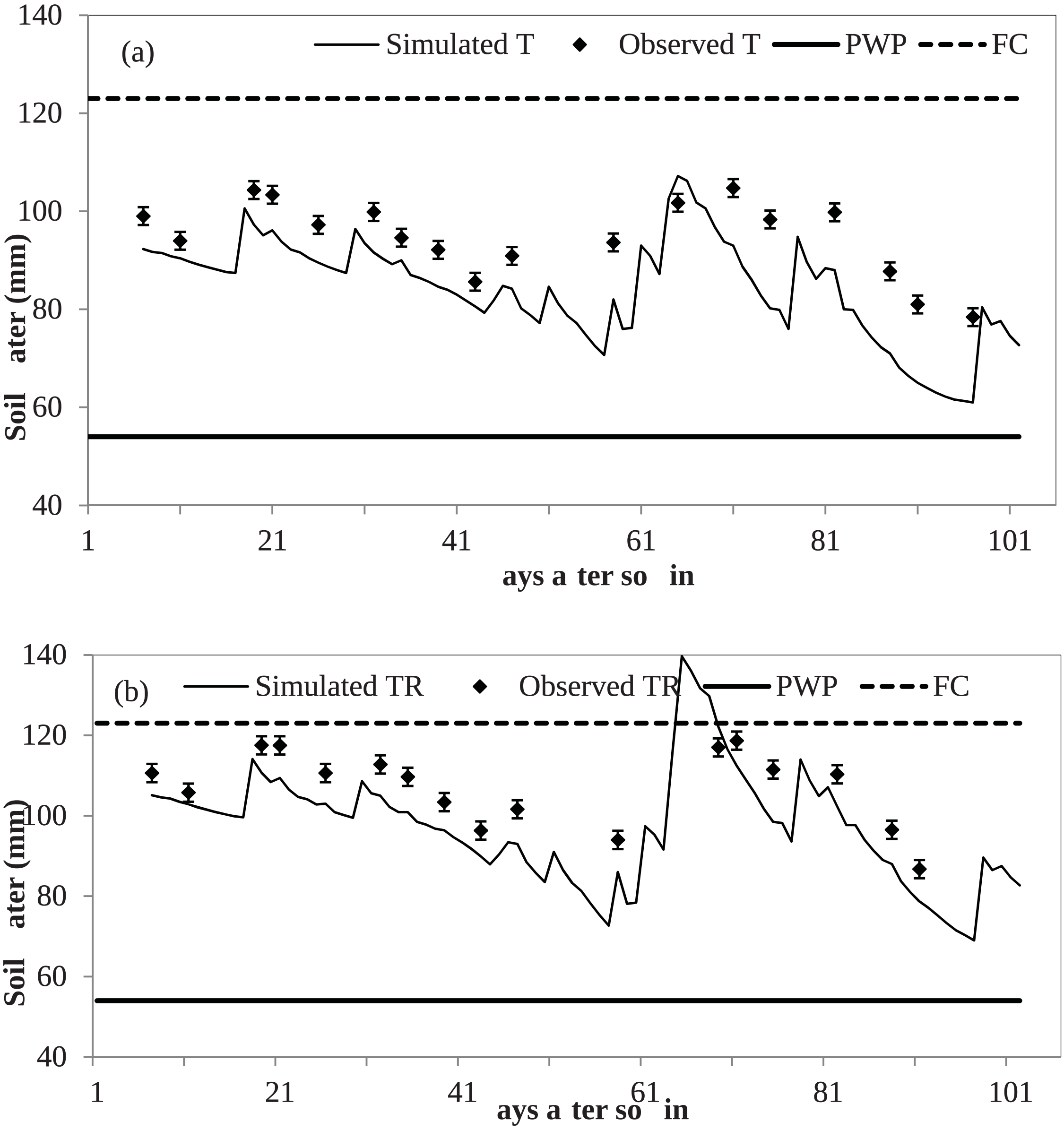

Figure 5.5. Simulated (lines) as compared to observed (diamond) soil water in the top 0.6 m soil under a rainfed maize with traditional tillage, T (a) and tied-ridges, TR (b) both without fertiliser during 2010 in Langano, Ethiopia. PWP, permanent wilting point; FC, field capacity.

5.3.2 Response of tied-ridges and improved soil fertility to different rainfall patterns

5.3.2.1 Amount of rainfall during the growing season

Given the current soil fertility level (46%), the application of tied-ridges improves the grain yield of maize up to 60%, with a long-term average (30 years) of 13%. When the total rainfall during the growing season is between 280 and 330 mm, the effect of tied-ridges on grain yield of maize is greater than improving the fertility level of the soil (Figure 5.6a). The difference in the simulated maize yield (total biomass or grain yield) between the tied-ridges and traditional tillage decreases with increase in the total rainfall during the growing season until the difference is zero or negative after about 650mm (5% probability of exceedance) (Figure 5.6a&b). More than 88% of the seasonal rainfall during the last 30 years was less than 580 mm. Thus, a negative effect of tied-ridges on maize yield is less likely. However, at the current soil fertility level, the soil water held in the tied-ridges remains underutilised during above average rainfall seasons. When the fertility level of the soil is improved from the current fertility level (46%) to 71%, the use of tied-ridges shows a continuously greater simulated yield (biomass or grain) of maize than with the traditional tillage. Combining tied-ridges and soil improvements to a 71% fertility level increases the simulated grain yield of maize by 30-207% depending on the amount of seasonal rainfall, with a long-term average of 63%. During the 2010 growing season, addition of farmyard manure (4.5 Mg ha^{-1}) in combination with tied-ridges improved maize grain yield by 47% while tied-ridges in isolations improved the yield by 26%. Generally, the effect of combining tied-ridges with fertiliser use tends to be higher during higher rainfall seasons than that during low rainfall seasons (Figure 5.6).

The application of tied-ridges substantially increases the amount of the seasonal rainfall used for transpiration with a more pronounced effect under low rainfall conditions (Table 5.5). The effect of tied-ridges in improving transpiration increases substantially when the fertility level of the soil is increased from current 46% to 71% and 96%. Tied-ridges combined with optimum fertiliser can increase the Grain-water use efficiency (G-WUE) of maize by 80-100% depending on the seasonal rainfall (Table 5.6).

Table 5.5. Percent of increased transpiration due to tied-ridges in response to different amounts of seasonal rainfall and soil fertility levels in Langano, Ethiopia.

Rainfall probability of exceedance (%)	‡Increment (%) in simulated transpiration due to tied-ridges at different levels (%) of soil fertility		
	46% (current)	71% (halfway to full recommendation, attainable)	96% (full recommendation, optimal)
80% (dry year)	24.0	39.9	43.6
50% (normal year)	7.8	14.5	17.9
20% (wet year)	3.2	7.5	9.9

‡ Increment (%) = (simulated transpiration from tied-ridges – simulated transpiration from traditional tillage) × 100/ simulated transpiration from traditional tillage.

Table 5.6. Grain-water use efficiency (G-WUE) in response to different amounts of seasonal rainfall, tied-ridges and improved fertility level.

Rainfall probability of exceeding (%)	Grain-WUE (kg ha^{-1}mm^{-1})						% increase [(TR96-T46)*100/T46]
	T46	TR46	T71	TR71	T96	TR96	
80% (dry year)	6.1	7.3	7.7	9.6	8.3	11.0	80%
50% (normal year)	6.9	7.1	10.4	11.1	12.1	13.9	101%
20% (wet year)	6.5	6.8	9.0	10.7	10.7	12.9	98%

T46, traditional tillage with current soil fertility level (46%); TR46, Tied-ridges with current fertility level; T71, traditional tillage with soil fertility increased to 71% (halfway to the full recommendation); TR71, tied-ridges with 71% fertility level; T96, traditional tillage with 96 % soil fertility level (optimal conditions, full recommendation); TR96, Tied-ridges with 96% soil fertility level; Grain-WUE, the ratio of simulated maize grain yield (kg ha^{-1}) to the total rainfall during the growing season (mm).

5. 3.1.2 Number of rainfall days during the growing season

Field observation of surface runoff during 2009 and 2010 revealed that runoff is triggered when there is a rainfall amount of around 12 mm per day. Moreover, the total rainfall during the growing season is more related (R^2 = 0.81) to the number of days with rainfall of greater than 12 mm day^{-1} than with the total number of wet (> 0.85 mm) days (R^2 = 0.52). At the current soil fertility level, simulated yield (total dry matter or grain) from tied-ridges is superior to the yield under traditional tillage until the number of days with rainfall of greater than 12 mm day^{-1} is around 21 (Figure 5.7). At fertility level of 71%, simulated yield from tied-ridges is always superior to the yield from traditional tillage.

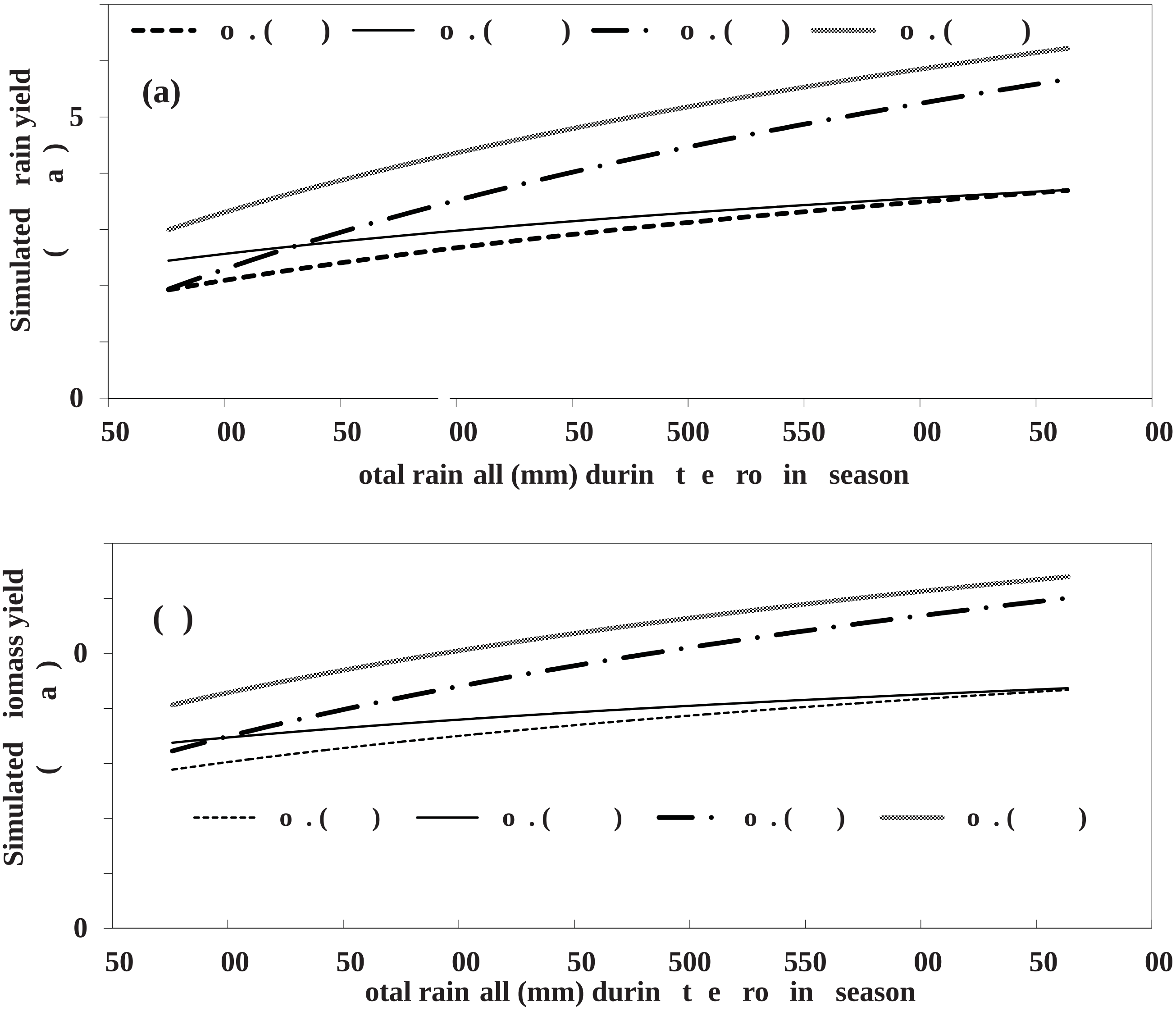

Figure 5.6. Simulated maize grain yield (a) and total above ground biomass (b) treated with traditional tillage (T) or tied-ridges (TR) in response to different amount of rainfall during the growing season and different fertility levels in the CRV, Ethiopia. T46, traditional tillage with current soil fertility level (46%); TR46, Tied-ridges with current soil fertility level; T71, traditional tillage with 71% soil fertility level; TR71, tied-ridges with 71% fertility level. Equations for the trend lines are presented in table 5.7.

Table 5.7. Trend line equations between simulated yield (biomass or grain, dependent variable y) and rainfall patterns during the growing season (x) according to different tillage techniques (traditional or tied-ridges) and different fertility levels in Langano, Ethiopia.

Rainfall pattern (independent variable, x)	Tied-ridges or traditional tillage	Equations			
		Dependent variable biomass yield		Dependent variable grain yield	
		At the current (46%) fertility level	Fertility level improved to 71 %	At the current (46%) fertility level	Fertility level improved to 71 %
Total rainfall during the growing season (figure 5.6)	Traditional	3.31ln(x) - 12.82	6.34ln(x) - 29.16	2.01ln(x) - 9.39	4.26Ln(x) - 21.98
	Tied-ridges	2.26ln(x) - 5.93	5.32ln(x) - 21.76	1.43ln(x) - 5.60	3.67ln(x) - 17.65
Number of rainfall days (figure 5.7)	Traditional	2.21ln(x) + 1.60	4.57ln(x) - 2.33	1.49ln(x) - 1.03	3.41ln(x) - 4.94
	Tied-ridges	1.48ln(x) + 3.93	3.79ln(x) + 0.8718	1.10ln(x) + 0.23	2.85ln(x) - 2.71
Date of sowing (onset, figure 5.8)	Traditional	$-1E\text{-}05x^3 + 0.004x^2 - 0.400x + 18.366$	$-2E\text{-}05x^3 + 0.005x^2 - 0.504x + 21.642$	$-9E\text{-}06x^3 + 0.003x^2 - 0.296x + 10.869$	$-2E\text{-}05x^3 + 0.005x^2 - 0.519x + 17.824$
	Tied-ridges	$-7E\text{-}06x^3 + 0.002x^2 - 0.186x + 11.039$	$-1E\text{-}05x^3 + 0.003x^2 - 0.202x + 10.709$	$-9E\text{-}06x^3 + 0.003x^2 - 0.291x + 11.371$	$-1E\text{-}05x^3 + 0.003x^2 - 0.273x + 9.4589$

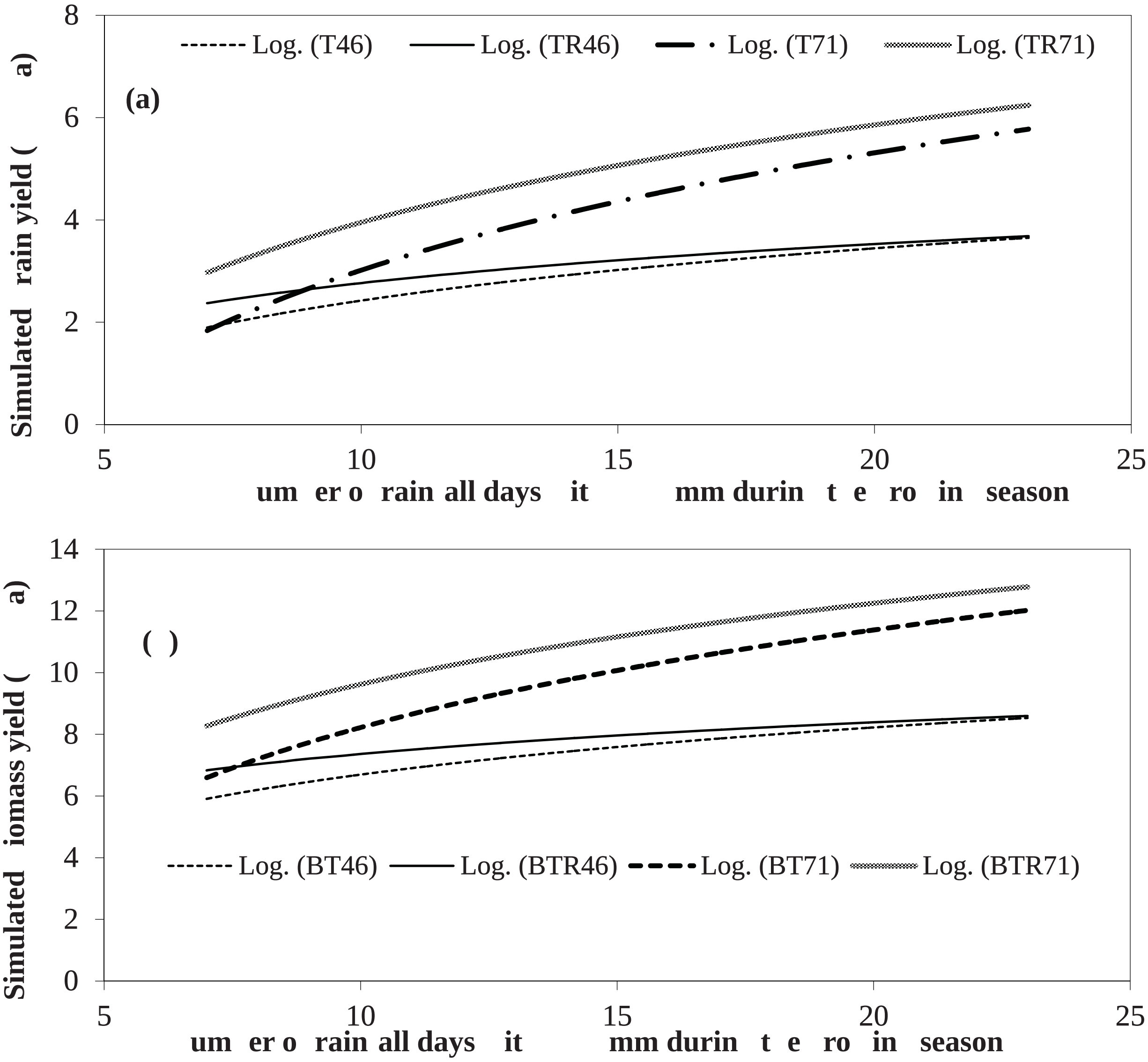

Figure 5.7. Simulated maize grain yield (a) and total above ground biomass (b) treated with traditional tillage (T) or tied-ridges (TR) in response to different number of days with rainfall of greater than 12 mm and different fertility levels in the CRV, Ethiopia. Equations for the trend lines are presented in table 5.7.

5.3.1.3 Sowing time (onset)

The date of sowing, which is determined by the onset of the rainy season, affects the yield response of tied-ridges and soil fertility improvement (Figure 5.8). At the current soil fertility level, simulated maize yield from tied-ridges is always superior to the maize yield under traditional tillage although the effect decreases from April to June (Figure 5.8). The long-term simulation revealed that the use of tied-ridges is better than improving the fertility level of the soil when planting is early, before the mid of April. The simulated grain yield of maize tends to be more sensitive to time of sowing than the simulated biomass yield as it is shown by the more twisted trend line in Figure 5.8a than that in Figure 5.8b. The simulations revealed that the month of May is the best time of sowing either with the traditional or improved technologies. The expected maize grain yield with specified probabilities of exceedance in response to the use of tied-ridges and improved soil fertility is presented in Table 5.8. When planting is done in April with a fertility level of 71%, the simulated yield from tied-ridges can be as much twice as that from the traditional tillage (Table 5.8).

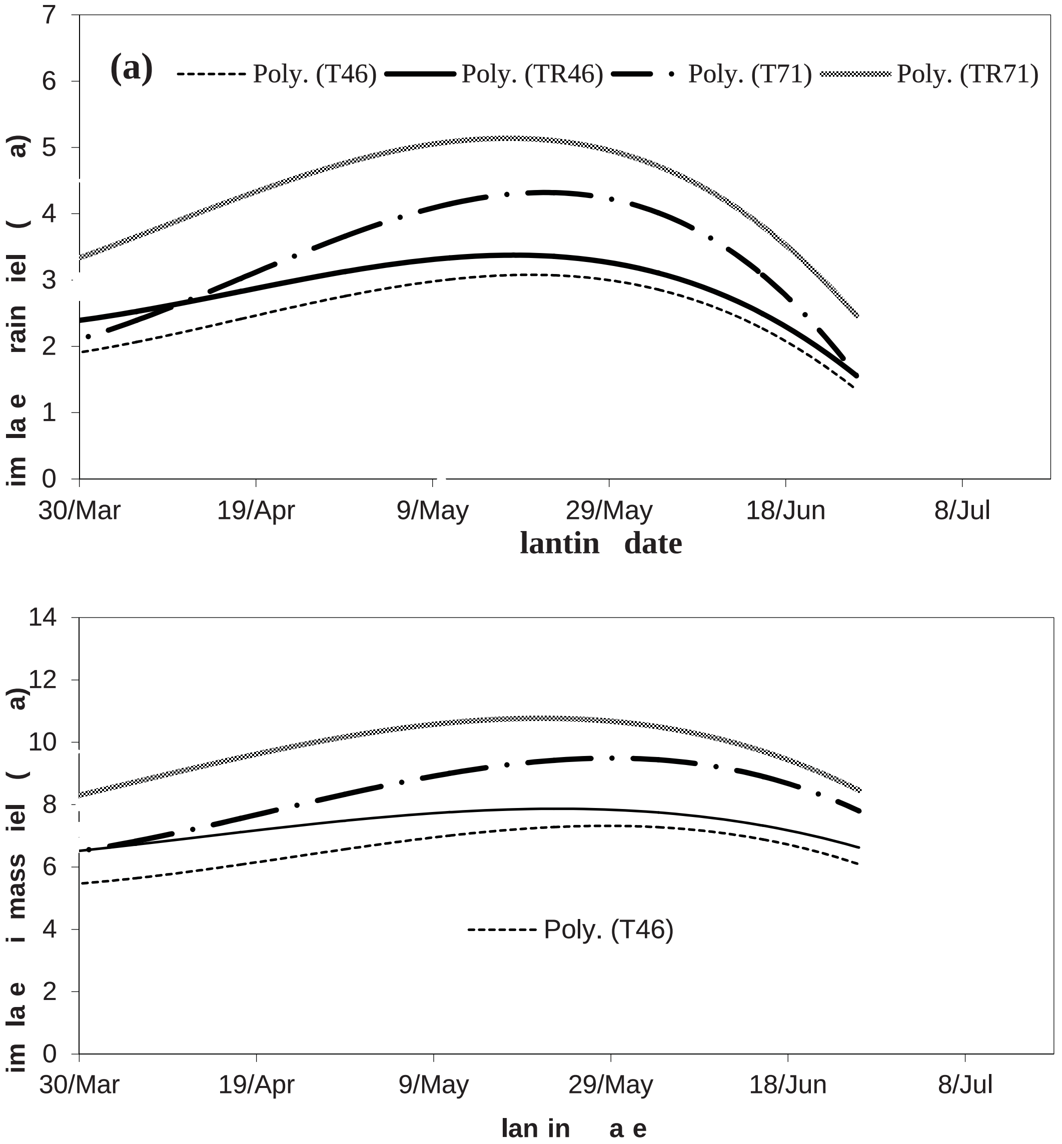

Figure 5.8. Simulated maize grain yield (a) and total above ground biomass (b) treated with traditional tillage (T) or tied-ridges (TR) in response to different planting dates and fertility levels in the CRV, Ethiopia. Equations for the trend lines are presented in table 5.7.

Table 5.8. Expected maize grain yield (Mg ha^{-1}) with specified probabilities of exceedance in three different sowing months in response to tied-ridges and fertilizer uses in Langano, Ethiopia.

Sowing Month	Type of Tillage	Maize yield probability of exceedance at the current fertility level (46%)			Maize yield probability of exceedance at 71% fertility level		
		20% (high)	50% (normal)	80% (low)	20% (high)	50% (normal)	80% (low)
April	T	3.2	2.7	2.1	5.4	3	1.8
	TR	3.5	3.0	3.0	5.6	5.1	4.4
May	T	3.6	3.0	2.5	5.6	4.3	3.1
	TR	3.7	3.4	2.8	6.1	5.2	4.4
June	T	3.6	2.6	1.5	5.3	3.1	1.4
	TR	3.6	3.1	1.6	6.0	3.7	2.0

All simulations were made only for those seasons when the total rainfall during the maize growing season (sowing-harvest, 120 days) was > 280mm; T, traditional tillage; TR, tied-ridges

5.4 Discussion

The FAO's AquaCrop model was able to simulate the canopy cover, root zone soil water and crop yields fairly well after calibration of the soil fertility level, a slight adjustment to one conservative parameter and determination of user-specific crop parameters for the local maize in the CRV of Ethiopia. The values of RMSE, percent deviation, and coefficient of determination (r^2) for the model validation were all in a similar range with previous simulations for maize by Heng et al. (2009), Hsiao et al. (2009) and Mhizha (2010). Being simple and robust, the AquaCrop model can be used for scenario analyses and as a decision support tool for planning and development of appropriate rainwater harvesting and management techniques. Hence, it was possible to recommend tying or untying of ridges and soil fertility improvements in response to different rainfall patterns in the Rift Valley drylands of Ethiopia.

The better effect of tied-ridges under low rainfall conditions than under higher rainfall conditions is in line with previous studies by Araya and Stroosnijder (2010). In the Ilambilole area of Tanzania where the soil is somewhat coarser (74-80% sand), Jensen et al. (2003) reported a significant increase in maize yield due to the application of tied-ridges. However, Wiyo et al. (2000) revealed that the effect of tied-ridges on maize yield improvement is meagre under a coarse-textured soil with a slope of 1.3% in Malawi. This is because more than 80% of the gained rainwater due to tied-ridges is lost as drainage below the root zone due to the coarse nature of the soil. In the shallow sandy loams of the CRV with an impermeable layer at 0.6-0.7 m depth and with a slope of 2.5%, the simulated maize yield under tied-ridges is higher than that under traditional tillage until there is about 650 mm seasonal rainfall (5% probability of exceedance) at which point the effect tends to be zero or negative.

Maize is moderately sensitive to water logging that reaches anearobiosis point when the root zone soil water status is at about 5-10% below the saturation point (FAO, 2009b). But, long-term water logging is less likely in the semi-arid CRV of Ethiopia where rainfall is erratic and the probability of long wet spells is low compared to the high probability of dry spells (Biazin and Sterk, 2011). However, during above average rainfall seasons, the excess water held in the tied-ridges remains underutilised (Figure 5.6). Thus, the higher simulated yield from combined use of tied-ridges and improved soil fertility compared to use of tied-ridges in isolation indicates a more effective utilization of the conserved rainfall. This is in line with the findings by Jensen et al. (2003) that revealed enhanced crop yield gains when fertiliser was combined with tied-ridges during above normal rainfall seasons in Tanzania. Meyer et al. (1987) also reported that additional supply of nitrogen to maize plants under waterlogged conditions could improve maize growth and yield. However, Ashraf and Rehman (1999) indicated that addition of higher amounts of nitrogen fertiliser at the start of long-term (about 21 days) waterlogged conditions has an adverse effect on maize shoot development.

In arid and semi-arid regions of Ethiopia where both the total amount and frequency of rainfall occurrence is low, heavier rainfall events make up a significant percentage of the total seasonal rainfall (Tilahun, 2006). At the current soil fertility level, the gap in simulated maize yield between the tied-ridges and traditional tillage decreases as the number of days with a rainfall amount of greater than 12 mm increases. This is in line with a previous study by Heluf (2003) who reported that the yield response of tied-ridges was higher in seasons with poorly distributed rains than in seasons with well distributed rainfall. The conserved soil moisture can be best utilized when the fertility level of the soil is improved from the current (46%) to near-optimal (71%) or optimal (96%) conditions.

Despite the weak correlation between onset and total rainfall during the growing season (r = 0.17), the effect of tied-ridges and improved soil fertility levels on simulated maize yields varied with different dates of sowing. The higher simulated yield in response to sowing in May as compared to early sowing in April or late sowing in June is likely attributed to the lower probability of long dry-spells between mid-July and mid-August (Biazin and Sterk, 2011) which are the flowering and grain-filling stages of the local maize that is planted in May. The higher effect of tied-ridges on simulated grain yield for early sowing in April as compared to that for sowing in May can be explained by the effect of the tied-ridges in mitigating the adverse of effects of dry spells on yield reduction. A previous study in Northern Ethiopia indicated that tied-ridges could keep the root zone soil water status just above the threshold of minimum for consecutive days thus mitigating the effect of short dry spells on barley (*Hordeum vulgare*) yield (Araya and Stroosnijder, 2010). Although late onset of the rains is the primary reason for late sowing of maize, delayed sowing of maize could be also caused by resource constraints such as draft power, lack of seeds in time, or shortage of labour particularly for women-headed households (Biazin and Sterk, 2011; Shumba, 1992).

Improving water use efficiency in arid and semi-arid areas can be achieved either by increasing the amount of water available for transpiration and/or by increasing the efficiency with which transpired water produces more biomass (Wallace, 2000). Given the poor fertility level of the Rift Valley drylands in Ethiopia, the use of tied-ridges to reduce surface runoff and increase available soil water for crops showed a perceptible increase in the simulated transpiration particularly during below average rainfall seasons (Table 5.5). On the other hand, during above average rainfall seasons, transpiration can be increased when tied-ridges are combined with increased soil fertility. The summer (June–September) rainfall pattern in Ethiopia is governed primarily by El Niño-Southern Oscillation (ENSO) and secondarily by local climatic indicators (Korecha and Barnston, 2007). Therefore, accurate predictions for ENSO within a short lead time to the summer season could be helpful for decisions regarding application of fertiliser in combination with tied-ridges to aptly exploit the seasonal rainfall.

The substantial increase in maize yield due to the combined application of tied-ridges and farmyard manure (4.5 Mg ha^{-1}) during a normal rainfall in 2010 implied the enhanced utilisation of the soil moisture held in the tied-ridges. Considering the availability of farmyard manure in the mixed crop–livestock systems in the CRV of Ethiopia, there is ample opportunity for soil improvements thus enhancing crop water uptake capacity. A combined application of manure and *zai* pits in Burkina Faso resulted in a more than twofold grain yield, compared with that obtained without manure (Fatondij et al., 2006). In the Rift Valley drylands of Kenya, the use of 4 Mg ha^{-1} farmyard manure in combination with tied-ridges was also beneficial in terms of reasonable crop yield and net benefit since the cost was lower than that of using expensive inorganic fertiliser (Kipkech and Kipserem, 2001). The same study reported that the application of inorganic fertiliser during low rainfall years (< 300mm) or during years with extended dry-spells could have either meagre or negative effects. For many small-holder farmers in the semi-arid tropics, it is simply not worth investing in fertilization (and other external inputs) as long as the risk of crop failure remains a reality every fifth year with risk of yield reductions every second year, due to periodic water scarcity (Rockstrom et al., 2002). In Ethiopia, smallholder farmers do not want to invest in fertilisers due to the risk of crop failure from erratic rains and dry spells. This leaves them trapped in low return, low risk agriculture (Dercon and Christiaensen, 2011). Therefore, mitigating agricultural water scarcity through the use of appropriate rainwater harvesting techniques may give farmers the confidence to invest in soil improvement techniques for improved crop production in dryland regions.

5.5 Conclusion

The poor sandy loam soils and unreliable rainfall conditions in the CRV of Ethiopia keep the question of how to achieve improved and sustainable agricultural production in the forefront. Field observations during the maize growing seasons of 2009 and 2010 revealed that between 18 and 30% of the rainfall may be lost in the form of runoff under the traditional tillage system. After proper calibration of the soil fertility level and field validation of the FAO’s AquaCrop model, it was possible to simulate the effect of tied-ridges on maize yield and water use efficiency in response to different rainfall patterns and fertility levels. The simulated maize yield due to the applications of tied-ridges and fertility improvements varies with the amount of rainfall, number of rainfall days and time of sowing. During low rainfall seasons (280 - 330 mm), the use of tied-ridges gives better results than improving the fertility level of the soil. During above average rainfall seasons, the excess water held in the tied-ridges can be best utilised by increasing the fertility level of the soil. Combined use of tied-ridges and farmyard manure has positive effects on maize yield under a wide range of rainfall amount and sowing dates. The Grain-WUE of maize can be doubled with the combined application of tied-ridges and optimum soil fertility. Since both agricultural water and soil fertility are limiting to maize productivity in the CRV, development of integrated rainwater harvesting and soil fertility improvement measures should be considered. The introduction and appropriate implementation of rainwater harvesting techniques may encourage farmers to invest in soil improvements for improved crop production in dryland regions. Additionally, this research showed that the *Maresha*-modified ridger can be popularized among Ethiopian farmers owing to its simplicity and effectiveness. Further research is recommended to examine the effect of planting density, response thinning, and supplemental irrigation through macro-catchment rainwater harvesting for improved rainwater use efficiency in the CRV of Ethiopia.

Chapter 6

Towards a participatory rainwater harvesting and management planning approach in the Rift Valley drylands of Ethiopia

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Towards a participatory rainwater harvesting and management planning approach in the Rift Valley drylands of Ethiopia

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Abstract

Despite extensive efforts of rainwater harvesting and management interventions for moisture-stressed and pastoralist areas in Ethiopia, the adoption and wider dissemination of the externally introduced techniques has been generally meagre. This is in contrary to the irreplaceable significance of rainwater harvesting and management (RWHM) in dryland agriculture. This paper explains a new participatory RWHM planning approach that has been proposed and tested for the development of in situ rainwater harvesting techniques in the Central Rift Valley (CRV) of Ethiopia. Existing practices and opportunities associated with in situ RWHM were identified. Based on a critical review, new potential in situ RWHM techniques were identified and illustrated to the farmers. Thereafter, the local farmers selected the most acceptable techniques and further suggested implementation procedures in relevance to their experiences and local opportunities. The existing practice of Dirdaro furrowing has been taken as a basis to introduce and develop tied-ridges. The most accepted techniques were, therefore, tested in the field for two consecutive growing seasons during 2009 – 2010 and their performances were evaluated. Overall, the participatory planning approach enables not only to utilise the existing knowledge and opportunities, but also empowers the farmers to select and introduce acceptable practices in accordance with their socioeconomic and environmental settings.

6.1 Introduction

Agricultural water management is central to improved agricultural production and ensuring food security in the predominantly rainfed agricultural systems of sub-Saharan Africa. Rainwater harvesting and management (RWHM) techniques are promising to exploit the full potential of the smallholder-based rainfed agriculture in dryland regions (Rockström et al., 2010; Rosegrant, 1997; Sachs et al., 2004). There are a range of RWHM techniques being practiced in different parts of sub-Saharan Africa (Biazin et al., 2011a; WOCAT, 2010). The commonly applied RWHM techniques in the region are either indigenous or modified from the indigenous techniques (Critchley et al., 1994; Liniger et al., 2011; Reij et al., 1996). For instance, *zai* pits in Burkina Faso, *Ngoro* pits in Tanzania, *tassa* in Niger and *Magun cultivation* in Sudan have different modes of application although all of them are aimed at preparation of planting pits for moisture conservation (Malley et al., 2004; Mupangwa et al., 2006; Reij et al., 1996; WOCAT, 2010).

A review of the RWHM practices in sub-Saharan Africa revealed promising biophysical and socioeconomic performances (Biazin et al., 2011a). Micro-catchment and *in situ* rainwater harvesting techniques could improve the root zone soil water content by up to 30% thus mitigating the adverse effects of dry spells during critical crop growing seasons (Abdulkadir and Schultz, 2005; Araya and Stroosnijder, 2010; Makurira et al., 2009; Motsi et al., 2004). The application of macro-catchment rainwater harvesting techniques for supplemental irrigation can help reduce the risk of total crop failure due to long dry spells (Barron and Okwatch, 2005; Fox and Rockström, 2003). Dryland soils being mostly degraded and poor in fertility, the combined applications of rainwater harvesting and soil fertility improvements could improve the crop yields by up to six times as compared to the traditional systems (Fatondij et al., 2006; Jensen et al., 2003; Zougmoré et al., 2003). Socioeconomic assessments in Ethiopia and Tanzania revealed that economic circumstances were better for the users than the non-users of rainwater harvesting techniques (Awulachew et al., 2008; Hatibu et al., 2006). Moreover, the applications of rainwater harvesting could encourage smallholder farmers to shift from cereal-based farming to diversified crops, hence improving household food security, dietary status, and economic return.

Despite extensive efforts of rainwater harvesting and management interventions for moisture-stressed and pastoralist areas in Ethiopia, the adoption and wider dissemination of the externally introduced techniques has been generally meagre. In the Tigray region of Northern Ethiopia, the introduction and myopic implementation of several micro-dams for runoff harvesting and small-scale irrigation was not successful (Abera, 2004). There has been a lack of farmers' involvement at different levels of project planning and implementation. In the four Administrative regions of Ethiopia (Tigray, Amhara, Oromia and Southern region), about 340,000 underground rainwater tanks (cisterns) were constructed in the years 2003–2004 to promote supplemental irrigation of crops (Bekele et al., 2006). However, only 37% of these cisterns were operational by the end of 2004. In central and northern Ethiopia where there has been continuous efforts of soil conservation and rainwater harvesting, many farmers have developed negative attitudes towards externally introduced measures (Amsalu and De Graaff, 2006; Abera, 2004). The introduced soil and water conservation technologies in the western highlands of Ethiopia were also characterized by a majority of the sample farmers as highly labour-intensive, with difficult designs to construct, conflicting with the existing system and inapt to the existing land tenure system (Bewket, 2007; Bewket and Sterk, 2002). A review of RWHM in sub-Saharan Africa revealed that the types of introduced techniques and the way of implementations were more of the preference of the donors and projects than that of the farmers with respect to their socioeconomic and physical settings (Biazin et al., 2011a; Spaan, 2003). Generally, complexity, establishment costs and lack of fit with local practices are key reasons for the meagre achievements of introduced techniques (Biazin et al., 2011a).

Given that there are rich experiences of indigenous RWHM techniques and there were meagre success stories in the adoption and wider dissemination of introduced techniques, there is a need for a better planning approach. In such new approach, farmers should be actively engaged in the selection and choice of potentially applicable techniques. Full participation of the farmers at various levels of planning may address the socio-economic conditions that affect adoption of introduced rainwater harvesting techniques (Ncube et al., 2008). Involving farmers in the planning of soil and water conservation measures enabled the selection of options that were suitable to their physical and socio-economic conditions (Okoba et al., 2007; Tenge et al., 2007). There is a need to identify integrated rainwater harvesting systems and to utilise indigenous knowledge as a decision-support tool for appropriate planning (Mbilinyi et al., 2005). Apart from this, although farmers and pastoralists are endowed with vast indigenous knowledge of rainwater harvesting and management (Biazin et al., 2011a; Critchley, 1994), their technical know-how has some limitations which, therefore, need to be supported by local institutions (Rajabu, 2005). Integrating indigenous knowledge with scientific approaches was found important for a successful planning and development of appropriate RWHM (Nyssen et al., 2000). In northern Ethiopia, stone bunds could be popularised only after integrating them with the traditional knowledge of lynchets, locally called 'daget' (Nyssen et al., 2000). Hence, in this study a participatory rainwater harvesting and management planning approach has been formulated based on various research and development experiences (Biazin et al., 2011a; Lininger et al., 2011; WOCAT, 2007). With this new approach, it is foreseen that indigenous RWHM practices can be improved and appropriate new techniques can be introduced from elsewhere with possible modifications in accordance with the existing socioeconomic and biophysical settings.

The aims of this paper were, therefore, to describe a new approach for participatory RWHM planning and to show its application for *in situ* rainwater harvesting development in the Rift Valley drylands of Ethiopia. The new approach has been proposed to be used for an appropriate planning of all types of RWHM techniques encompassing macro-catchment and micro-catchment systems as well. Given the less complexity and relatively lower financial requirements in the planning and implementations of in situ RWHM techniques, they were used to test the applicability of the new approach. Upon testing its effectiveness, this approach may be aptly used in the future planning and development of rainwater harvesting and management techniques in the vast drylands of Ethiopia or elsewhere in sub-Saharan Africa where rainfed agriculture continues to be the main source of livelihood.

6.2 The new approach

6.2.1 Description of the participatory RWHM planning approach

The proposed approach will allow the farmers to actively engage at various phases of planning and development encompassing diagnosis of agro-meteorological challenges, identification of existing knowledge and opportunities, selection of potentially applicable new rainwater harvesting techniques, and field testing. Thus, this approach consists of six steps (Figure 6.1). It is assumed that local experts and development agents can apply it for an appropriate planning of RWHM techniques for an area of a certain agro-meteorological setting.

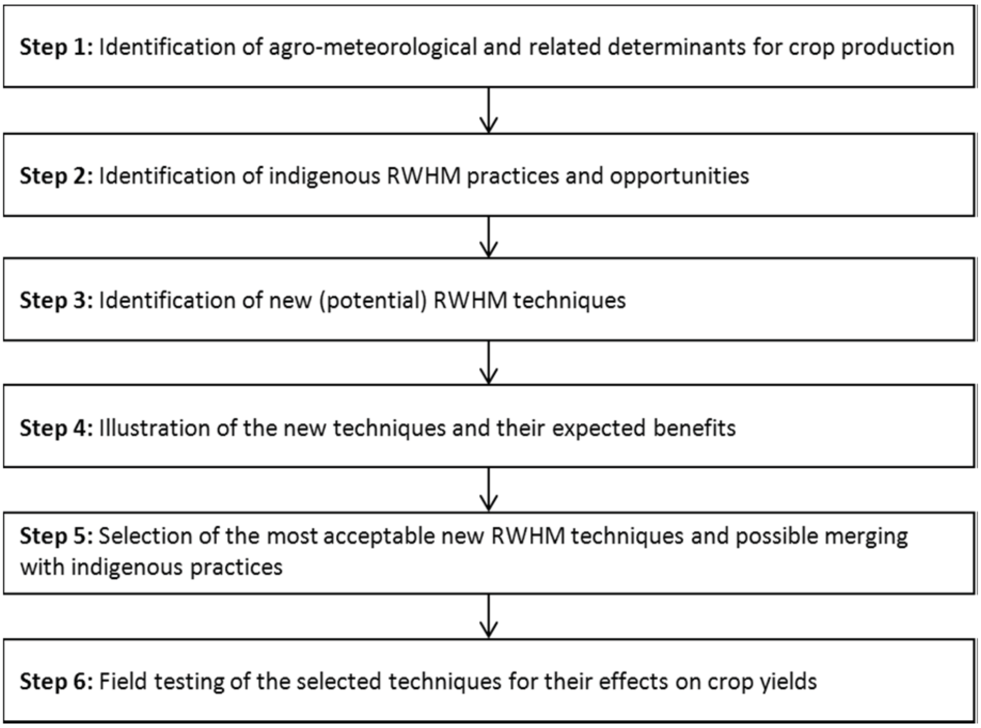

Figure 6.1. Schematic steps for a participatory rainwater harvesting and management planning approach.

Step 1: Identification of agro-meteorological and related determinants for crop production.
Assessing the perceptions of the local community to agro-meteorological determinants for crop production is crucial for an appropriate planning of rainwater harvesting techniques. The main causes of crop failure associated with water scarcity are identified through repeated meetings with key informants. Based on these meetings, a well thought out formal survey is developed and applied for a detailed understanding of the people's perceptions. Hence, the effect of different agro-meteorological factors (onset, dry spells, cessation and total amount of seasonal rainfall) on crop production are identified. Accordingly, the perceptions of the farmers to the frequency of either moderate or severe droughts caused by either of the aforementioned agro-meteorological elements can be assessed.

Expected outcome: list of farmers' priority agro-meteorological and related determinants for crop production.

Step 2: Identification of indigenous RWHM practices and opportunities
Many of the rainwater harvesting techniques in sub-Saharan Africa are traditional techniques or modified from traditional techniques (Critchley et al., 1994; Lininger et al., 2011; Reij et al., 1996). Any attempt to improve water productivity and water-use efficiency of a given agricultural system should, therefore, start with an inventory of current land management and rainwater harvesting practices (FAO, 2005). As a follow up of the survey used in step 1, semi-structured interviews with key informants followed by a formal survey is used to assess indigenous rainwater harvesting practices, land management techniques and associated soil improvement techniques that could enable improved agricultural water productivity. Apart from this, other opportunities (possibility of using mulch, compost, manure, etc.) that could be important to achieving improved crop productivity are assessed. Once the indigenous techniques and opportunities are identified, further improvements would be possible in later steps based on experiences from elsewhere.

Expected outcome: list of indigenous rainwater management practices and related opportunities

Step 3: Identification of new (potential) RWHM techniques through review of relevant sources.
Those RWHM techniques that have been found effective in dryland agriculture elsewhere in the world can be selected through review of secondary sources. Biazin et al. (2011a) outlined the various rainwater harvesting and management techniques and their biophysical and socioeconomic performances in sub-Saharan Africa. The various water harvesting techniques and their performances in Western Asia and Northern Africa have also been reported (Oweis and Hachum, 2006; Oweis et al., 2004; Oweis et al., 2001). Moreover, important toolkits like WOCAT (http://www.wocat.net), the works of Soil and Water management network (SWMnet), and International Water Management Institute (http://www.iwmi.cgiar.org) can be used for detailed understanding of the different techniques. Hence, the performance of the techniques elsewhere in the world, the similarities with the indigenous practices, agro-ecological similarity, and affordability with the existing farming systems are important considerations during the identification of potentially applicable new techniques. Therefore, in this study, an extensive review of the most commonly applied in situ and micro-catchment rainwater harvesting techniques along with their performances has been made (Tables 6.7 and 6.8). This may be used as an important database although further understanding of the different techniques may be sought by development agents.

Expected outcome: list of new (potential) rainwater harvesting and management techniques that may possibly be introduced.

Step 4: Illustration of the new techniques and their expected benefits.
Those techniques that have been identified in step 3 are illustrated with their expected benefits to the local farmers and discussed for final selection. Hence, a workshop is conducted with key informants representing different wealth classes, village leaders, representatives from the district and zonal offices of agriculture. In case the techniques are not easily understandable, practical demonstration or training of the participants about the techniques may be required. If possible, some key informants may even travel to places where those practices have been implemented and adopted by the local people. The key informants may suggest possible modification of the indigenous practices or merging of indigenous knowledge with the new techniques. The possibility of using local opportunities for RWHM development and possible combinations of RWHM techniques with soil improvements is also discussed thoroughly.

Expected outcome: the key informants understand the new techniques and their expected benefits clearly.

Step 5: Selection of the most appropriate RWHM techniques

The selection of the most appropriate RWHM techniques is conducted by those key informants who were fully involved during the illustration and demonstration of the new techniques in step 4. This is done in another workshop that should be undertaken immediately after the previous workshop. Thus the different modified indigenous and the new techniques will be ranked by the key informants. In this step, the facilitator should initiate all the key informants so that they will make equal voting in the process of ranking. For the most accepted techniques, the key informants may suggest appropriate procedures and modes of implementation in accordance with their existing biophysical and socioeconomic settings.

Expected outcome: list of RWHM techniques accepted for field testing and procedure of field applications.

Step 6: Field testing of the most accepted RWHM techniques

Facilitation of farmer-driven experimentation will allow farmers to methodically assess the value of the innovations they choose to study while providing researchers with a venue for learning about socioeconomic as well as biophysical influences on farmers' decisions (Sturdy et al., 2008; WOCAT, 2007). Before wider dissemination of the agreed upon techniques, a field trial is required to practically evaluate the benefits of the selected techniques on crop yields. The implementation of the selected techniques in the field follows the procedures that have been suggested and agreed upon by the key informants. The field evaluation of the selected techniques can be conducted for consecutive years on plots of volunteer (pilot) farmers. Repeating the field evaluations consecutively may enable to test the techniques in response to different patterns of seasonal rainfall. The number of pilot farmers may increase during the following years depending on their willingness. During the field evaluations, the key informants will visit the pilot fields repeatedly and make their judgements on the performances of the different techniques. The final crop yields must be determined at the end of each growing season for each of the RWHM techniques. Thus, comparisons of crop yields gained from the different RWHM techniques and the traditional system (control) should be done.

Expected outcome: quantified crop yields for the tested RWHM practices against the existing system.

6.2.2 Description of the study area

The participatory RWHM planning approach has been tested for in situ rainwater harvesting development in the Central Rift Valley (CRV) of Ethiopia. The study area is situated at about 190 km south of the capital Addis Ababa at longitude 38^{0}40 E and latitude 7^{0}33 N. The area lies with an altitudinal range of 1580-1660 above sea level and has an average slope of 2-3%. Aridity index, which is described as the ratio of annual precipitation to potential evapo-transpiration (P/ET_o), has been used to classify drylands in to arid, semi-arid and dry sub-humid lands (UNCCD, 2000; MEA, 2005). Accordingly, the study area is a semi-arid climate with an aridity index of 0.37 (P/ET_o). The annual rainfall varies between 270 and 960 mm (CV = 30%) with a mean of 650 mm for the past 30 years. Although the area was previously covered by dense acacia woodlands, which had been used by the pastoral Oromo people coming from the nearby highland areas, a significant proportion of the area is subjected to cultivation and grazing since the last five decades (Eshete, 1999). Major crops are maize (*Zea mays* L.) and haricot bean (*Phaseolus vulgaris* L.). Livestock includes mainly cattle and goats. Following crop harvests, livestock freely graze on the crop residues. Although cattle manure is abundant around homesteads where the households corral their livestock, most of the local farmers did not put any manure on their cultivated fields. The soil is poor in fertility and shallow with an impermeable calcite layer between 0.55 and 0.70 m. It readily compacts and is liable to crusting and drought (Biazin et al., 2011b).

6.2.3 Application of the approach

The participatory RWHM planning approach has been applied between 2008 and 2010 in the CRV of Ethiopia. During March – September, 2008, focused group discussions with selected stakeholders and semi-structured interviews with key informants were held and these discussions were followed by two socioeconomic surveys. The latter surveys were used to examine the socio-economic situations, determinants of crop production, the perceptions of the smallholder farmers to agricultural drought, current land management systems for rainwater management and opportunities for improved production. Agro-meteorological characterisation was done based on long-term weather data which was collected from the Langano Meteorological Centre that represents the study area. Following a thorough review of the various RWHM practices in sub-Saharan Africa (Biazin *et al*., 2011a), potential in situ techniques were selected and presented to the local farmers before the start of the 2009 growing season. Therefore, those techniques, which were accepted by the local farmers, were tested in plots of volunteer farmers during the 2009 and 2010 growing seasons. Crop yields for a local maize cultivar were determined on the plots with different RWHM techniques and compared with the existing traditional practice. For further scientific understanding, runoff, profile soil water content and rooting patterns were continuously monitored. An automatic weather station and a conventional rain gauge were installed onsite for meteorological data collection during the growing seasons. A detailed explanation of the field experimental setup is found in Biazin and Stroosnijder (2011).

6.3 Results

6.3.1 Agro-meteorological determinants, opportunities and indigenous practices (Steps 1 and 2)

According to the people's accounts, maize production in the CRV of Ethiopia is limited by agricultural drought due to unreliable rainfall (100% of the respondents, N=66), and resource constraints such as lack of fertilisers due to high prices (72% of the respondents) and poor access to improved seeds (55% of the respondents). In the CRV, being a poor or rich farmer is not only a matter of differences in the amount of livestock, and land, but also leads to differences in drought perceptions, use of networks and coping strategies (Kool, 2010).While rich households perceived the occurrence of drought every 7-10 years, the poor households perceived it within a range of 3 -5 years. Drought being the priority agricultural problem, late onset of the rains delaying sowing and long dry spells during the growing season were perceived as the major agro-meteorological constraints to crop production. Once the crop is planted, the length of consecutive dry days (dry spells) is the most perceived agro-meteorological determinant for crop production. The mean lengths of dry-spells that are critical to the growth of the local maize variety (*Awassa BH540*) at different developmental stages were identified based on the people's accounts (Table 6.1).

There are a range of land management practices that are used as in situ rainwater harvesting by the local farmers in the CRV (Table 6.2). Most of these techniques are associated with tillage, hoeing or soil management. Tillage during planting is carried out carefully in such a way that moisture conservation is possible. Before the introduction of line sowing of maize, tillage during sowing has been undertaken using the Malibes technique. The Malibes technique is practiced using the traditional Maresha plough by tilling the soil back and forth consecutively thus making the soil surface more or less flat. Recently, many farmers (67% of the respondents, N=64) adopted a new type of tillage, Dirdaro furrows, in association with line sowing. The Dirdaro furrows are made with the traditional Maresha plough after every two planting rows with an average of 50-54 cm intervals across the slope just after sowing. Hence, the furrows help to reduce runoff and enhance infiltration. Furthermore, during the Dirdaro tillage, the soil from the ridges is inverted to both sides of the planting rows, thus probably reducing soil evaporation from around the rooting zone. It has been widely applied in Northern Ethiopia (Nyssen et al., 2011).

Table 6.1. The perceived critical lengths of dry spells during the different developmental stages of maize in the CRV, Ethiopia.

Development stage (DAS)[†]	Critical lengths of dry spells
Emergence and establishment (1-25 DAS)	19
Vegetative developmental stage (26-60 DAS)	19
Flowering and grain filling (61-90 DAS)	7
Maturation stage and drying (91-120 DAS)	9

[†] *DAS, days after sowing*

The sandy loam soils of the Central Rift Valley in Ethiopia are easily crusted after every wetting and drying cycle which could limit infiltration and enhance soil evaporation (Biazin et al., 2011b). Removal of the surface crusts is practiced either by manual hoeing or traditional Shilshalo tillage using Maresha ploughing following every wetting and drying cycle during the Maize growing season. Manual hoeing is practiced once or twice during the first three weeks after sowing to loosen the thin soil surface. The Shilshalo ridging is practiced using the traditional Maresha plough on the furrows that were made for Dirdaro about 35-45 days after sowing. In the mixed crop-livestock farming system of the CRV, there is ample opportunity to exploit the abundance of farmyard manure. Few farmers (26% of the respondents, N=66) shift the location of corralling so that they can use the fertilised (manured) land for maize cultivation. The key informants claimed that application of farmyard manure can cause drying up of the crop particularly during low rainfall seasons. It could be associated with the fact that addition of too much manure causes faster vegetative and canopy growth that quickly exhaust stored soil moisture thereby increasing sensitivity to dry spells.

Table 6.2. Indigenous land management techniques that are used as in situ rainwater harvesting techniques in the CRV of Ethiopia.

Type of land management technique	Proportion of total respondents (%, N=66)	Time of application	Perceived effects on water conservation
Dirdaro furrows	67	during sowing of maize	Reduces surface runoff and enhances infiltration; makes seed covering easier during planting.
First manual hoeing	95	14-20 days after sowing	Breaks the surface crusts and loosens the soils; helps to pile soil around the root zone where soil evaporation can be reduced.
Second manual hoeing	71	21-35 days after sowing (usually applied as a replacement for *Shilshalo*)	Breaks the surface crusts and loosens the soils; helps to pile soil around the root zone where soil evaporation can be reduced.
Shilshalo ridging	100	30-45 days after sowing	Breaks the surface crusts and enhance infiltration; inverts the soil from the ridges to the root zone where soil evaporation can be reduced; helps to remove weeds.
Shifting the location of corralling	26	After 1-3 years of corralling	Enhances crop productivity due to increased fertility (with manure).

6.3.2 Identification and illustration of new (potential) techniques and their expected benefits (Step 3 & 4)

Identification of new potential in situ RWHM techniques for introduction into the CRV was made based on an extensive review of the RWHM experiences across the sub-Saharan Africa (Table 6.3). The most commonly applied in situ RWHM techniques in sub-Saharan Africa encompass ridging (tied or open), mulching, and other conservation tillage techniques (Biazin et al., 2011a). Mulching can be done with crop residues, grasses or stones and rock fragments. Ridging, sub-soiling and other conservation tillage (reduced tillage, zero tillage, etc.) are done with different types of tillage implements in different regions. However, tillage implements used in other African countries do not fit with the frames of the traditional plough in Ethiopia. Recently, there have been encouraging efforts to develop conservation tillage implements through modifications of the traditional Maresha plough in Ethiopia (MST, 2008; 2010). Therefore, the Maresha-modified ridger and Maresha-modified sub-soiler have been considered for the introduction of tied-ridges and sub-soiling in the CRV (Figure 6.2). The performances of the different in situ rainwater harvesting techniques were found spectacular when they were combined with soil improvement techniques such as addition of manure and compost (Jensen et al., 2003; Zougmoré et al., 2003). Hence, the possibility of using farmyard manure and composting as soil improvement techniques were also considered in the CRV.

A day-long workshop was undertaken to illustrate the new in situ RWHM techniques and their expected benefits for the key informants. Sub-soiling using the Maresha-modified sub-soiler, tied-ridging using the Maresha-modified ridger, and the preparation of compost were demonstrated to the key informants (Figure 6.3). Moreover, zero tillage or reduced tillage techniques were elaborated to the key informants and discussed thoroughly.


(a) (b)

Figure 6.2. (a) Maresha-modified ridger (MST, 2010), and (b) Maresha-modified sub-soiler (MST, 2008) for in situ rainwater harvesting in the CRV of Ethiopia.

Table 6.3. The new in situ RWHM techniques, their features and performances elsewhere as illustrated for the farmers in the CRV, Ethiopia.

Type of techniques	Regions of wider application	Climatic condition	Effect on crop yield[¥]		References
			Without fertiliser	With fertiliser	
Tied-ridges	Many parts of the SSA	Semi-arid, and dry sub-humid	19-44%	100-600%	Hulugalle (1990) Lal (1990) Wiyo et al. (1999) Jensen et al. (2003)
Sub-soiling	Western Africa	Semi-arid, dry sub-humid	1-25%	22-118%	Rockström et al. (2009)
Mulching	Western and Eastern Africa	Can be applied under wide climatic conditions	30-50%	-	Henseley et al. (2000) Tengberg et al. (1998) WOCAT (2010)
Reduced tillage	South Africa	Semi-arid, dry sub-humid, humid	10-50%	20-955	Rockström et al. (2009) Walker et al. (2005)
Zero tillage	Southern Africa	Semi-arid, dry sub-humid, humid	2-50%	20-95%	Rockström et al. (2009) Walker et al. (2005)

[¥] *Yield increment described as compared to the traditional system without the application of the technique and fertiliser*

Figure 6.3. Field demonstration and training on the Maresha-modified ridger in the CRV of Ethiopia.

6.3.3 Selection of the most appropriate RWHM techniques (Step 5)

Ranking of the different techniques was undertaken by the same key informants in another day-long workshop making use of a grouping technique (Figure 6.4). The key informants were divided into two groups of 8 persons each to check if they could have come up with different rankings. If they had come up with different rankings, it was intended to bring them together and figure out the cause of differences and make the most agreed upon ranking. In this study, however, both groups came up with similar rankings (Table 6.4). During the process of ranking, the facilitator tried to make sure that all the participants have made equal voting. Ranking of the new in situ RWHM techniques was done in comparison to the traditional tillage sytem to differentiate between the acceptable and unacceptable ones. Accordingly, those techniques which have been ranked after the traditional tillage sytem were considered not acceptable by the key informants.

Tied-ridging using the *Maresha*-modified ridger, sub-soiling using the *Maresha*-modified sub-soiler, addition of dry farmyard manure and addition of compost were ranked as better than the existing farming system (Table 6.4). Among the presented techniques, mulching, minimum tillage, and zero tillage were put after the traditional system by the farmers. Mulching was not accepted as an apropriate technique mainly because crop residue is desperately needed as source of feed for livestock during the dry season. Moreover, the key informants did not like reduced tillage and zero-tillage, rather they underscored that repeated tillage is essential for good crop production. This could be due to the prevailing problem of crusting in the sandy loam soils of the CRV (Biazin et al., 2011 b; Temesgen, 2007) which need to be prevented via continuous manipulations by tillage. Although farmyard manure has been rarely used for soil improvements in the area, after illustration of its benefits in dryland regions elsewhere it was ranked second to tied-ridges. The farmers put the major advantages and constraints of the different techniques in accordance with their biophysical and socioeconomic realities (Table 6.4). Following a lengthy discussion, the key informants suggested a procedure for the implementations of the selected techniques (Table 6.5). Regarding the distribution of farmyard manure, it was proposed to be made before the primary tillage so that it can be incorporated with the soil by subsequent tillage operations.

Table 6.4. Farmers' ranking of the in situ RWHM techniques and their possible constraints and advantages in the CRV of Ethiopia.

Type of introduced technique	Order of ranking	Suggested advantages/opportunities	Suggested constraints
Tied-ridges	1	Tying of the ridges will help to reduce runoff; with the new ridger, it is possible to make wider ridges than the D*irdaro* furrows.	Difficulty to apply *shilshalo* with it; the new implement incurs additional cost.
Use of dry farmyard manure	2	Improve crop yields; unlike other parts of Ethiopia, dry farmyard manure is not used as a source of household energy due to better access for the acacia woodlands for firewood and charcoal from the woodlands.	It may initiate drying up of the maize crop when applied either in fresh or damped particularly during dry seasons.
Sub-soiling	3	Could be used to loosen the soil deeper than the traditional tillage and enhance infiltration of rainfall.	Difficulty to apply cross-ploughing during consecutive tillage operations; purchase of the subsoiler incurs additional cost.
Compost	4	Improve crop yields; availability of the ingredients (leaves and crop residues, manure, soil) for composting.	Difficulty of getting water for the preparation; bad smelling may not be good for health.
Traditional tillage	5	Easy to practice and no extra expense is required.	Not good enough to conserve moisture.
Mulching	6	Enhance infiltration of rainfall and cover the soil from the sun.	Mulch is desperately needed as source of feed for livestock during the dry seasons.
Reduced tillage	7	May be applied when onset is late.	Without repeated tillage crop yield declines.
Zero tillage	8	No suggested advantage.	Without tillage crop yields can be very low.

Figure 6.4. Key informants ranking the new in situ rainwater harvesting techniques in order of acceptance in the CRV of Ethiopia.

Table 6.5. Proposed procedures of land preparation & sowing according to the selected in situ rainwater harvesting techniques in the CRV of Ethiopia.

Land preparation and sowing	*In situ* techniques		Traditional tillage
	Sub-soiling	Tied-ridges	
Primary tillage	Traditional *Maresha* ploughing followed by *Maresha* -modified sub-soiling on every other furrow	Traditional *Maresha* ploughing	Traditional *Maresha* ploughing
Secondary tillage	Traditional *Maresha* ploughing followed by *Maresha* -modified sub-soiling on the previously sub-soiled furrows	A cross ploughing using the traditional *Maresha* plough followed by tied-ridging using the *Maresha* -modified ridger on every other furrow. The ridges are tied every 4 meters.	A simple cross-ploughing using the traditional *Maresha* -plough
Sowing	Sowing is undertaken on the previously sub-soiled rows after ploughing by the traditional Maresha. The soil inversion is undertaken according to the traditional *Dirdaro* technique using the traditional *Maresha* plough	Sowing is undertaken on the previously ridged rows after ploughing by the traditional *Maresha* plough. The soil inversion is undertaken according to the traditional *Dirdaro* technique using the *Maresha*-modified ridger. The ridges are tied every 4 meters.	Sowing is undertaken after ploughing across the secondary tillage. The soil inversion is undertaken according to the *Dirdaro* technique using the traditional *Maresha* plough.

6.3.4 Field performances of the selected RWHM techniques (Step 6)

During the 2009 and 2010 growing seasons, the effect of the selected techniques on maize yield was determined on farm plots of four volunteer farmers. Therefore, the tied-ridges, sub-soiling and traditional tillage were made according to the procedures suggested by the key informants (Table 6.5). The implementation of tied-ridges was done based on a simple modification of the existing *Dirdaro* practice. The *Maresha*-modified ridger made 26 cm wide ridges while the traditional *Dirdaro* tillage made 20 cm wide furrows at the surface of the soil. Both the tied-ridges and the traditional *Dirdaro* tillage systems had a similar furrow depth of 16 cm. Previous efforts of developing tied-ridges in Ethiopia used manual widening of the ridges and tying which required extra labour (Araya and Stroosnijder, 2010; McHugh et al., 2007; Nyssen et al., 2011). With the new ridger, ridges are tied easily by raising the ridger at constant intervals of about 4 m. This is approximately five paces while plowing. Dry farmyard manure (4.5 Mg ha^{-1}) was distributed and incorporated by the primary and secondary tillage operations.

The key informants visited the pilot fields repeatedly during the 2009 and 2010 growing seasons. During the 2009 growing season, there was a dry spell length of 30 days (rainfall < 1 mm) which was far greater than the perceived critical lengths of dry spells (Table 6.1). Moreover, the total rainfall during the whole growing season was very low. As a result, the yield of maize was disappointingly low. The key informants claimed the year as a drought year. Given the negligible differences in maize performances between the in situ RWHM techniques and the traditional system, they perceived that the selected techniques are not beneficial to rescue the crop from severe droughts. They suggested introduction of supplemental irrigation techniques that can rescue the crop from long dry spells. The use of farmyard manure improved maize yield somehow even during this very dry year. During the 2010 growing season, there were no consecutive dry days exceeding the perceived critical lengths (Table 6.1). Based on their experiences, the key informants claimed the 2010 growing season as a good year. The total rainfall during the whole growing season was also near to long-term average. The yield of maize was highest due to the combined use of tied-ridges and farmyard manure. An optimum use of farmyard manure has shown promising benefits under both very low and normal rainfall conditions. Following a final meeting during the harvest of the 2010 growing season, the key informants agreed to continue testing the combined use of farmyard manure and tied-ridges at a larger scale. But sub-soiling was recommended to be tested at a lower scale given that its perceived benefit was less promising. They became more enthusiastic to effectively exploit farmyard manure for improved crop production. The effect of the selected techniques on crop performances during above normal rainfall seasons is yet to be investigated. The performance of maize during the two growing seasons in response to the different in situ RWHM and their combinations with farmyard manure has been statistically analysed (Table 6.10).

6.4 Scientific justifications and discussions

6.4.1 Agro-meteorological challenges, and opportunities (Steps 1 and 2)

Considering the perceived criteria of drought, long-term meteorological analyses revealed that long-dry spells caused 2 severe and 6 moderate drought years while late onset of the rains caused 5 severe drought years for maize out of the last 28 years (Biazin and Sterk, 2011; Table 6.1). Figure 6.5 depicts the probability of dry spells that have been perceived by the local farmers as critical to maize during the different developmental stages (Table 6.1). The probability of occurrence of a dry spell length of 7 days or more is generally high throughout the maize growing season although the local farmers underscored that it is critical for maize particularly during its flowering time. Hence, the adverse effects of these dry spells need to be mitigated through appropriate in situ RWHM techniques. Moreover, there is a reasonable gap between the long-term mean dekadal (ten days) precipitation and reference evapo-transpiration (ETo), particularly during the months of May and June (Table 6.6). The inter-annual variability of dekadal rainfall is painfully high during the maize growing season implying unreliability of the rainfall. Apart from this, the total rainfall during the growing season is more correlated (r = 0.89) with the number of days with a rainfall of greater than 12 mm than with the total number of rainy days (r = 0.4). Hence, the higher probability of dry spells and the erosive nature of the rainfall infers feasibility of in situ rainwater harvesting techniques associated with runoff harvesting.

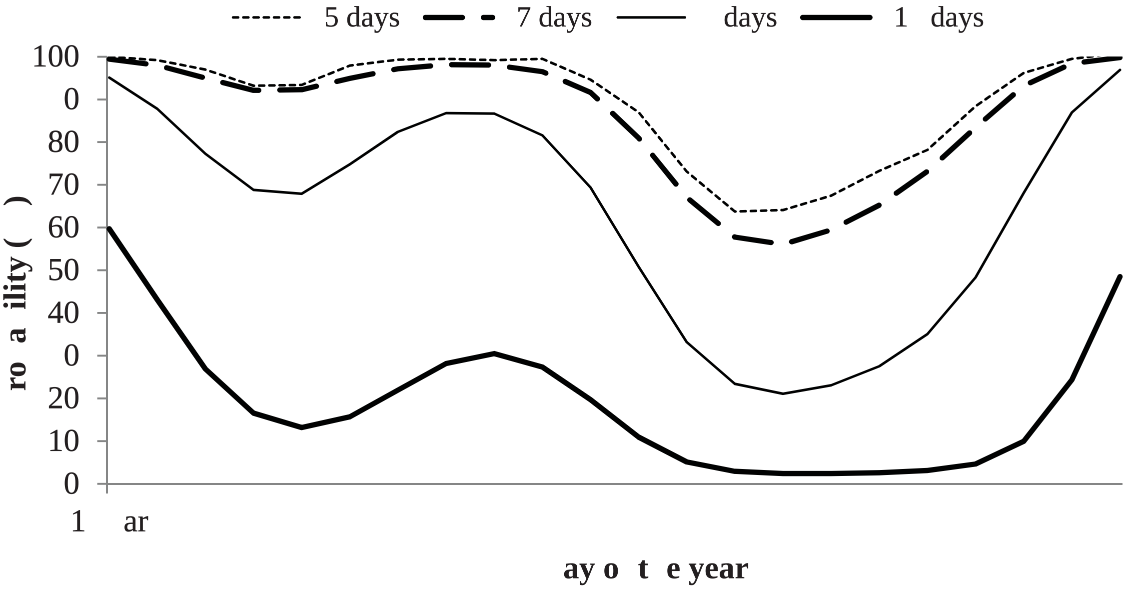

Figure 6.5. Probabilities of dry spells exceeding 5, 7, 9 and 19 days in Langano, the CRV of Ethiopia.

Table 6.6. Long-term mean dekadal (ten days) rainfall (RF) and Reference Evapo-transpiration (ETo) during the maize growing season in the CRV, Ethiopia.

Month	Dekad of the month	RF		Mean ETo (mm)	RF-ETo (RF/ETo)$^{€}$
		Mean	CV (%)		
May	1	25	136	51	-26 (0.49)
	2	33	120	50	-17 (0.66)
	3	20	138	52	-32 (0.38)
June	1	23	100	48	-25 (0.48)
	2	29	125	47	-18 (0.62)
	3	33	96	45	-12 (0.73)
July	1	47	65	43	4 (1.09)
	2	45	85	42	3 (1.07)
	3	48	66	41	7 (1.17)
August	1	42	74	42	0 (1.00)
	2	41	78	43	-2 (0.95)
	3	37	66	44	-7 (0.84)
Total		423	-	548	-125 (0.77)

$^{€}$*Values in parenthesis are meant for the ratio of dekadal precipitation to reference evapo-transpiration.*

Table 6.7. Micro-catchment rainwater harvesting – Overview of the most common practices with their features and performances.

Name and description	Specific practices	Countries of current application	Main crops	Yield gains (%) without soil amendments	Yield gains (%) with soil amendments	Environmental features			References
						Agro-climate/rainfall	Soil conditions	Terrain conditions	
Pitting: A series of planting pits is dug across plots; the shape and dimensions of the pits may be different.	*Zai* pits	Burkina Faso	Maize, Sorghum	50-150	200% -600 (with manure or compost)	Arid and semi-arid areas	Crusted desert soils; Sandy to sandy loams	Flat to gently slopes	Fatondji et al. (2006) Kabore and Reij (2004)
	T*assa* pits	Niger	Maize, Sorghum	50-100	300 - 400 (with manure or compost)	Arid and semi-arid areas	-	Gentle slopes	Haggblade et al. (2004) Kabore and Reij (2004) Reij (1996)
	Ngoro pits	Tanzania	Maize	> 28	-	Semi-arid and dry sub-humid areas	Sandy to clay	Moderate to steep slope	Malley et al. (2004)
	Trenching	Ethiopia, Tanzania	Grasses, perennials, cereals	44	-	Semi-arid and dry sub-humid areas	Preferably deep soils	Gentle to moderate slopes	WOCAT (2010)
Micro-basins: Different shapes of small basins, surrounded by low earth bunds or stone lines are formed to make the runoff infiltrate at the lowest point, where plants are grown.	Negarims (diamond), Eye-brows and half-moon (semi-circular)	Ethiopia, Israel, Libya	Mainly for grasses and perennial crops	30- 100	200- 1000 (the highest from stone lines and compost in Burkina Faso)	Arid, semi-arid or dry sub-humid areas with erratic rainfall	Preferably deep soils to enhance infiltration	Moderate to gentle slopes	Abdulkedir and Schultz (2005) Renner and Frasier (1995a; 1995b) Zougmoré et al. (2003)
Contouring: The technique of putting soil, stone or strip of unploughed land or vegetation along the contour in a cultivated hill-slope to conserve soil and water.	Stone and soil bunds:	Ethiopia, Kenya, Tanzania. South Africa.	Cereals (Maize and sorghum)	5-15	-	Semi-arid and dry sub-humid areas with erratic rainfall	Preferably in rocky/ston soils, but other soils as well except very shallow soils	Gentle to moderate slopes	Herweg and Ludi (1999) Spaan (2003) Vancampenhout et al. (2006)
	Hedge rows and vegetation barriers	Burkina Faso	Cereals (Maize and Sorghum)	-	-	In arid and semi-arid areas	-	Preferably in gentle slopes	Kiepe (1995a) Spaan (2003)
Terracing: Bunds in association with a ditch, along the contour or on a gentle lateral gradient are constructed in different forms.	*Fanya Juu*	Kenya, Ethiopia, Tanzania	Cereals (Teff, wheat, barley, maize, etc.)	25-50	-	Preferably in semi-arid, dry sub-humid or humid areas	Preferably in deeper soils	Moderate to steep slope	Gebremedihin et al (1999); Tengberg et al. (1998); WOCAT (2010)
	Bench terraces	Kenya, Ethiopia, Tanzania, China	Mainly for grasses and perennial crops	25-150	-	-	Shallow and degraded soils	Steep slopes	Biamah et al. (1993) Tengberg et al. (1998) WOCAT (2010)

Table 6.8. In situ rainwater harvesting: Overview of the most common practices with their features and performances.

Name and description	Specific practices	Countries of current application	Main crops	Yield gains (%) without soil amendments	Yield gains (%) with soil amendments	Environmental features			References
						Agro-climate/rainfall	Soil conditions	Terrain conditions	
Ridging: Tillage techniques With basins usually larger than traditional furrows. They can be tied every 3-6 m distance for holding water and facilitating infiltration in low and erratic rainfall areas.	Open ridges or furrows (Terwah, Shilshalo, Dirdaro, etc.)	Ethiopia	Cereals (teff, Sorghum, Maize, etc.)	10-33	-	Semi-arid and dry sub-humid areas	Variable soil conditions	Gentle to moderate slopes	Araya and Stroosnijder (2010) Nyssen et al. (2011)
	Tied-ridges	Tanzania, Malawi, Ethiopia,	Cereals (teff, Sorghum, Maize, etc.)	20-44	100 - 400	Semi-arid and dry sub-humid areas	Variable soil conditions	Gentle to moderate sloping	Araya and Stroosnijder (2010) Jensen et al. (2003) Wiyo et al. (1999)
Mulching: The use of both crop residues and material from non-cultivated areas, including stones and plastics. This improves infiltration of water into the soil and prevents evaporation out of the soil	Crop residue mulch	South Africa, Zimbabwe, Kenya	Cereals (Sorghum, Maize, etc.)	10-50	-	Semi-arid, dry sub-humid and humid areas	-	Preferably gently sloping	Henseley et al. (2000) Tengberg et al. (1998) WOCAT (2010)
	Stone mulching	Ethiopia	Cereals (teff, wheat, barley, etc.)	5-10	-	-	Soils with available rock fragments and stones	Preferably in gentle slope	Nyssen et al. (2000) WOCAT (2010)
	Plastic mulching	China	-	20-22	-	-	-	Preferably in gentle slopes	Li et al. (1999)
Conservation tillage: It encompasses a wide range of tillage techniques ranging from non-inversion ploughing and reduced tillage to ripping and sub-soiling in moisture-stressed areas.	Sub-soiling, ripping	Kenya, Ethiopia, South Africa	-	2-20	20-95	Semi-arid and dry sub-humid areas	Mainly in soils liable to compaction or plough pans	-	Rockström et al. (2009) Temesgen (2007)
	Reduced tillage	Kenya, South Africa Ethiopia	Maize	5-50	-	Mainly in dry sub-humid areas	Soils with good organic matter content	-	Aune et al. (2011) Itabari et al. (2011) WOCAT (2010)

6.4.2 Identification of potential rainwater harvesting techniques and illustration of their benefits (Steps 3 and 4)

Identification of the most appropriate rainwater harvesting techniques for introduction to a given area is one of the most important and yet difficult steps in the new approach. Although there are some toolkits and scientific papers that have documented about a range of rainwater harvesting techniques, a summary outline of these techniques based on their feature, suitable environmental settings, types of crops used and expected benefits in isolations or in combination with soil improvements should be accessible for development agents. When the new techniques are presented and illustrated to the farmers, they need to be well-acquainted with the way of implementation and expected benefits. A clear illustration of the new techniques will enable farmers to suggest possible modifications based on their experiences, biophysical setting and socioeconomic conditions for an appropriate implementation. Therefore, as part of the rainwater harvesting research project, an extensive review of the most commonly applied in situ and micro-catchment rainwater harvesting techniques along with their important features and performances was made (Tables 7 and 8). These tables show that spectacular gains in crop yields can be obtained from appropriate combinations of rainwater harvesting and soil improvements. This implies that for an effective adoption by smallholder farmers, development agents need to find ways to integrate RWHM interventions with appropriate soil amendment techniques as much as possible. However, the expected benefits of the different techniques according to all agro-meteorological conditions is yet to be done for adequate selection of possibly introduced techniques. This could be achieved through appropriate model simulations.

In this project, the effect of tied-ridges on maize rainwater use efficiency and yield was simulated with the FAO's AquaCrop model (Biazin and Stroosnijder, 2011). Relative to other sophisticated models, the FAO's AquaCrop requires fewer parameters and input data to simulate the yield response to water and nutrients for most of the major field crops cultivated worldwide (Steduto et al., 2009). After proper calibration and validation of the model, it was possible to predict the effect of tied-ridges on maize yield in response to different patterns of rainfall (onset, amount and distribution) and soil fertility levels. Simulation in response to planting of maize during different months in the CRV of Ethiopia revealed that tied-ridges are more effective when applied for sowing during April than for sowing during May and June (Table 9). The outcomes of simulations based on long-term meteorological data revealed that combining tied-ridges and soil improvements can increase maize yield by more than double as compared to the traditional system. Although tied-ridges caused water logging effects during above normal rainfall years elsewhere in sub-Saharan Africa (Jensen *et al*., 2003), it is less likely in the CRV of Ethiopia where consecutive wet days are less probable and the soil is dominantly sandy loam. Accordingly, upon proper calibration and validation of the FAO's AquaCrop model in different regions of Ethiopia, it could be possible to put a database with the full scenario about the expected benefits of different rainwater harvesting techniques in response to different rainfall patterns and fertility levels.

Table 6.9. Simulated maize yield with tied-ridges and traditional tillage systems according to different planting months in the CRV, Ethiopia.

Planting month (onset)	Simulated maize yield (Mg ha^{-1})					
	Traditional tillage			Tied-ridges		
	Current fertility level (46%)	Near-optimal fertility level (71%)	Optimum fertility level (96%)	Current fertility level (46%)	Near-optimal fertility level (71%)	Optimum fertility level (96%)
April	2.3	3.2	3.5	2.8	4.3	5.0
May	2.8	4.0	4.6	3.1	4.9	6.0
June	2.7	3.8	4.4	2.9	4.5	5.5

6.4.3 Field evaluation of the new techniques (Step 6)

Field investigations were done to make scientific explanations about the effect of the selected techniques on maize productivity and rainfall partitioning during the 2009 and 2010 growing seasons. The 2010 growing season had a normal rainfall (46% probability of exceedance) while 2009 had a very low rainfall (96% probability of exceedance). Hence, a split plot design was implemented on four farmers' fields where tied-ridges, sub-soiling and traditional tillage with *Dirdaro* were put as the main plots. The main plots were split into two sub-plots of farmyard manure applications: 4.5 Mg ha^{-1} and no manure. Although maize yield is the main parameter for the farmers, additional monitoring was done on surface runoff, soil water content of the maize rooting zone and rooting patterns for scientific justifications.

Maize yield was significantly ($\alpha < 0.05$) higher under plots treated with either farmyard manure or tied-ridges than the control with traditional tillage during a normal rainfall season in 2010 (Table 10). The interaction effect of manure application and tied-ridges on maize yield was also significant ($\alpha < 0.05$). During the very dry season of 2009, the use of the *Maresha* modified tied-ridges and sub-soiling did not improve maize productivity ($\alpha > 0.05$) whereas dry farmyard manure improved the maize productivity significantly ($\alpha < 0.05$). Hence, this implies that as long as the dry farmyard manure is fairly distributed during the offseason, the perception of the local people to manure as a cause for drying up of maize is not acceptable. This is in line with the perceptions of the key informants who concluded that the selected techniques can be beneficial during good years such as 2010 and not beneficial during drought years such as 2009.

Depending on the rainfall intensity and antecedent soil moisture, the proportion of the rainfall that was lost in the form of runoff ranged from 18 to 30% (24% on average) from the traditional tillage, from 15% to 28% (22% on average) from sub-soiling and from 0 to 7% (3%) from tied-ridges during the 2010 growing season (Figure 6.6). This is in line with a previous study by McHugh et al. (2007) who reported that 15% of the rainfall was lost as runoff on average from a traditional tillage system in the clay loam soils of Wollo region in Ethiopia. Moreover, Araya and Stroosnijder (2010) revealed that 15-30% of the rainfall could be lost as runoff from slopes of 0-3% in the silt loam soils of Tigray region in Ethiopia. Another study in the Rift Valley of Ethiopia has also reported that up to 40% of the seasonal rainfall may be lost in the form of surface runoff non-productively thus reducing the productive 'green' transpiration (Welderufael et al., 2008). The traditional *Dirdaro* furrow, which is made across the slope during sowing, is targeted to trap surface runoff. The observed benefit of tied-ridges in improving maize yield is a justification of the erosive nature of the rainfall and its importance for trapping a significant proportion of the surface runoff that could have been lost non-productively.

Table 6.10. Maize grain yield determined according to different in situ RWHM techniques during 2009 and 2010 growing seasons in the CRV, Ethiopia.

Year and total rainfall*	Type of technique	Mean grain yield (Mg ha^{-1})		Benefits (percent)[₱]	
		With manure	Without manure	With manure	Without manure
2010 (420 mm)	Traditional tillage (control)	3.5(±0.12)bx	2.7(±0.10)by	30	-
	Tied-ridges	4.0 (±0.2)ax	3.4(±0.1)ay	48	26
	Sub-soiling	3.7(±0.28)abx	3.0(±0.14)aby	37	11
2009 (230 mm)	Traditional tillage (control)	0.5(±0.1)ax	0.3(±0.1)ay	67	-
	Tied-ridges	0.5(±0.09)ax	0.3(±0.1)ay	67	-
	Sub-soiling	0.5(±0.1)ay	0.4(±0.1)ay	67	33

**Values in parentheses refer to total rainfall during the growing season of maize from sowing to harvest. Standard error of the mean in parentheses and mean values followed by similar letters a-c along a column of a given year or x-y across a row are not significantly ($\alpha = 0.05$) different. [₱]Benefits were computed as ((yield from introduced technique – yield from the control)/ yield from the control) x 100.*

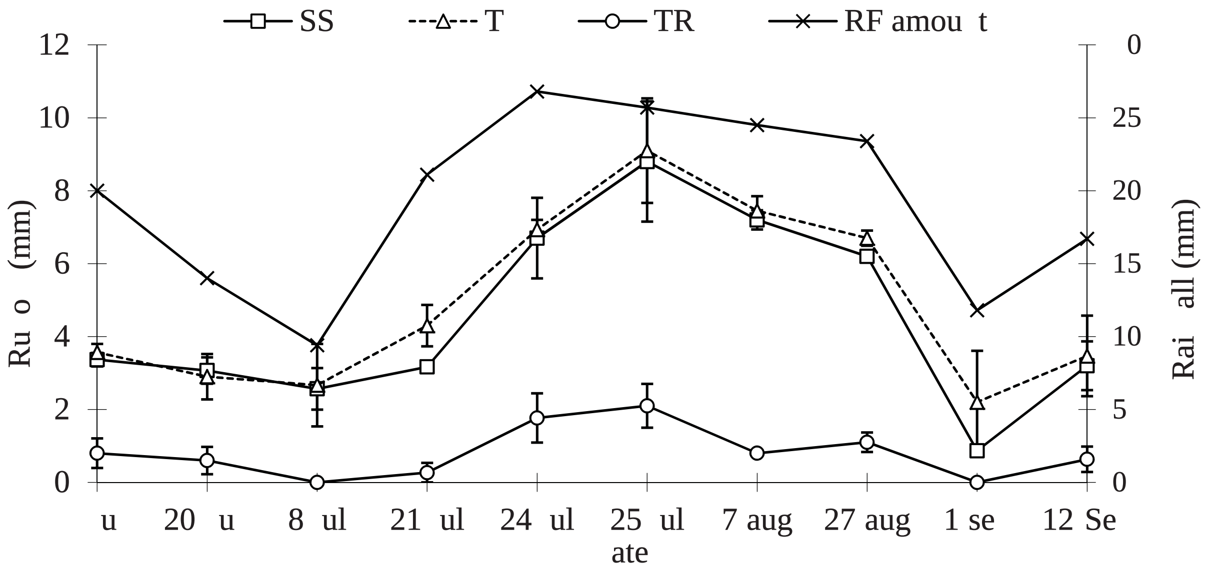

Figure 6.6. Runoff (mm) observed under Tied-ridges (TR), Sub-soiling (SS) and Traditional tillage with Dirdaro (T) from a maize field in 2010 in the CRV of Ethiopia. Standard error of the mean indicated as error bars for mean runoff. During the 2009 growing season, only three rainfall events could produce runoff. Hence, runoff amounts of 2.5 mm from rainfall of 14 mm (July 7), 4.5mm from rainfall of 27.1mm (July 14), and 2.3 mm from rainfall of 15mm (July 20) were measured from the traditionally Dirdaro tillage.

Soil water content of the maximum rooting zone (0.6 m) was improved by 10.9% due to tied-ridges and by 3.3% due to sub-soiling on average during the 2010 growing season. However, during the 2009 growing season, the effect of tied-ridges (2.3%) and sub-soiling (1.5%) on soil water improvements were negligible. The effect of the different techniques on soil water improvements was different at different depths of the soil. The soil water content of the top 0-15 cm soil depth was on average 15.4% larger under tied-ridges and 3.1% larger under sub-soiling than the traditional tillage. In the 15-30 cm soil depth, the soil water content was 12.1% larger under tied-ridges and 3.7% larger under sub-soiling than the traditional tillage on average. Within the 30-45 cm soil depth, the soil water status was 7.3% and 2.8% higher under the tied-ridges and sub-soiling as compared to the traditional tillage respectively.

Root length density (RLD, cm cm^{-2}) was significantly ($\alpha < 0.05$) higher due to tied-ridges than that due to sub-soiling and traditional tillage with *Dirdaro* at the top 0-15 cm soil depth (Figure 6.7). At the 16-30 cm soil depth, the RLD under sub-soiling was significantly higher ($\alpha < 0.05$) than that under the tied-ridges and traditional tillage. However, there was no much difference in the RLD below 30 cm soil depths. The application of dry farm manure (4.5 Mg ha^{-1}) could improve the RLD (average for 0-60 cm depth) by 37-48%.

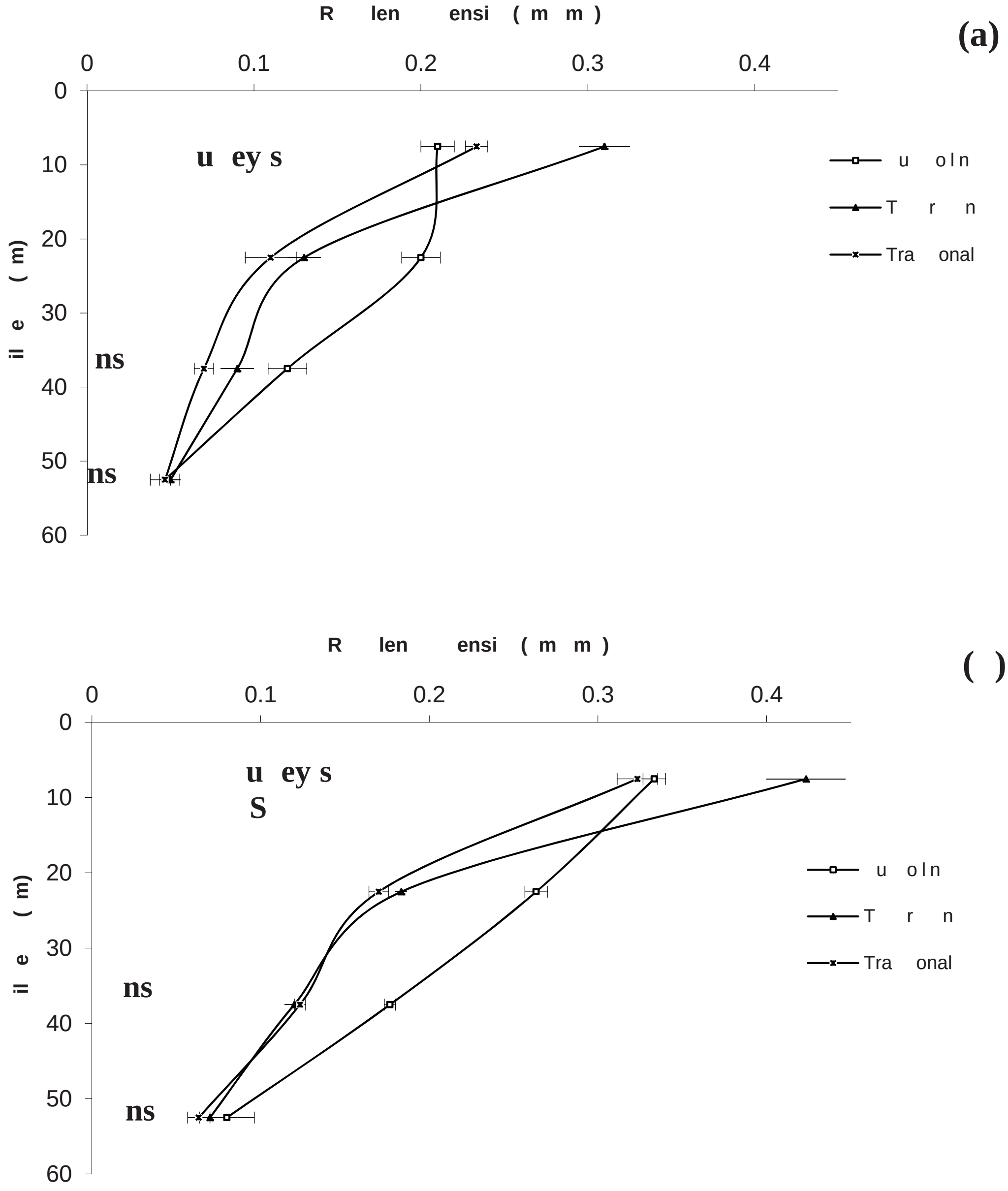

Figure 6.7. Effect of different in situ RWHM techniques on root length density (cm cm^{-2}) at different soil depths (0-15cm, 16-30cm, 31-45cm and 46-60cm) without farmyard manure (a) or with farmyard manure applications (b) in the CRV of Ethiopia. Mean separations with the Tukey's HSD is implied by "" for significant differences and by "ns" when there are no significant differences (α = 0.05).*

6.5 Conclusion and research needs

The participatory RWHM planning approach was proposed and tested for an introduction of in situ rainwater harvesting techniques in the CRV of Ethiopia. The approach starts with investigation of the priority agro-meteorological determinants for crop production and identification of the existing knowledge and opportunities. The proposed approach also enables to plan with an integration of rainwater harvesting and soil improvement techniques. The application of this new approach in the CRV implied that any effort on the introduction of new in situ rainwater harvesting techniques needs to assess the existing tillage, hoeing and associated land management practices. In the CRV of Ethiopia, the existing *Dirdaro* furrow system could be taken as a basis to introduce and develop tied-ridges using the *Maresha*-modified ridger. Moreover, the poor fertility level of the sandy loam soils requires soil improvement techniques thus implying the possibility of using the abundant farmyard manure for an effective exploitation of the rainfed agriculture. For an effective adoption of rainwater harvesting techniques by farmers, integrated rainwater harvesting and soil improvement techniques should be applied as much as possible. It was concluded that the introduced in situ rainwater harvesting techniques can improve crop yields except in very dry years. Overall, this approach may augment the recent efforts of dissemination of RWHM techniques for improved agricultural development in the vast drylands of Ethiopia. For a better implementation of the proposed approach, further research is needed in the following areas.

In this project, the most commonly applied in situ and micro-catchment rainwater harvesting techniques across SSA have been outlined with their typical features and performances based on an extensive review. However, the expected benefits of these techniques in response to all agro-meteorological settings and soil characteristics should be further assessed and availed as database for development agents who might apply the new participatory planning approach. Model simulations may replace the expensive and long-term field testing to simulate the expected effects of the various RWHM techniques in response to different rainfall patterns and soil conditions. Upon proper calibration and validation the FAO’s AquaCrop model for different crops could be used to explore the benefits of the various RWHM techniques in a given agro-meteorological and soil conditions. Hence, further research support is needed.

The performances of the introduced techniques in improving crop yields cannot be the prime factor for a wider dissemination and implementation. As a follow up of the participatory planning approach, socioeconomic impacts assessment tool is required for proper dissemination and promotion of the best performing techniques. Hence, further research is needed to develop an appropriate dissemination approach.

Although the new participatory planning approach was tested for in situ rainwater harvesting techniques, it was proposed to be applied also for micro-catchment and macro-catchment RWHM techniques. Therefore, further testing might be necessary on these techniques.

Chapter 7

Synthesis

Synthesis

Given that rainfed agriculture is the mainstay of Ethiopian economy, annual crop yields are unacceptably low and variable due to seasonal shocks by drought and dry spells (Bewket, 2009; Tesfaye and Walker, 2004). At a national scale, average grain yields of major cereal crops are in the range of 1 to 2 Mg ha^{-1} on smallholder rainfed farms (CSA, 2010; De Graaff et al., 2011). Erratic nature of the rainfall, long dry seasons, and recurrent droughts and dry spells are common phenomena, particularly in the vast drylands of Ethiopia that cover about 65% of the country (Seleshi and Zanke, 2004; Tilahun, 2006). To keep in pace with the growing demand for food, cereal yields in Ethiopia should grow to 4.5 Mg ha^{-1} by 2030 (Metaferia, 2009). There is a potential to reach cereal yields of 5 to 8 Mg ha^{-1} from rainfed agricultural systems through appropriate and integrated applications of water, soil and crop management techniques (FAOSTAT, 2005; Rosegrant et al., 2002; Seyoum et al., 1998). Although soil improvements might give higher yield gains due to the current poor fertility levels of dryland soils, most smallholders are not willing to invest in fertilizers due to the risks of crop failure by erratic rains and dry spells (Dercon and Christiaensen, 2011). Hence, reducing these risks through appropriate rainwater harvesting and management techniques can encourage farmers to invest in soil improvements and other productivity enhancement techniques (Rockström et al., 2010).

The intention of this study was, therefore, to evaluate and develop appropriate rainwater harvesting techniques for improved and sustained agricultural production in the drought-prone Central Rift Valley (CRV) drylands of Ethiopia. The study was commenced by assessing the experiences of rainwater harvesting practices across sub-Saharan Africa and exploring the performances of most commonly applied practices. Thus, the most important opportunities and major challenges for further development were identified. In order to be able to zoom-in, drought vulnerability and the changing trends in land-use and land management techniques were assessed in the CRV. The temporal changes in soil water properties in response to land-use conversion from woodlands to crop cultivation and long-term conventional tillage using the traditional *Maresha* plough were also examined. Following a participatory selection of new techniques and incorporation of existing knowledge and opportunities, field experimentation was combined with model simulation. Following proper calibration and validation of the FAO's AquaCrop model, it was possible to simulate the effect of tied-ridges and soil fertility improvements on maize water use efficiency and yield gains in response to different patterns of rainfall. Meteorological data of the last three decades were used for drought analyses and model simulations. These studies were put into place to answer the original research questions.

1) What are the common rainwater harvesting and management techniques in drought-prone sub-Saharan Africa, and how have they performed? (Chapter 2)
2) How does drought vulnerability determine the dynamics of land-use/cover and development of better land management techniques? (Chapter 3)
3) What are the long-term implications of the conventional Maresha ploughing on soil water properties in the Rift Valley drylands of Ethiopia? (Chapter 4)
4) Can the FAO's AquaCrop model be used to examine the effect of rainwater harvesting techniques on crop yields in response to different rainfall patterns ? (Chapter 5)
5) What is the most appropriate approach to stimulate adoption of RWHM measures in the current farming system of the CRV drylands? (Chapter 6)

In this final chapter, the major findings of the chapters 2 through 6 and their scientific insights and developmental implications are presented in contrast to current knowledge. Be they contradictory or supplementary to the existing knowledge, the new insights of this study will be instrumental in the efforts to improve agricultural productivity in the vast drought-prone drylands of Ethiopia.

7.1 Rainwater harvesting in sub-Saharan Africa: opportunities and challenges

This study showed that sub-Saharan Africa (SSA) is in fact the birthplace of many indigenous rainwater harvesting and management (RWHM) techniques - some of which have even been introduced to west Asian drylands (Chapter 2). Farmers have traditionally evolved and adapted to ever-changing environments by developing diverse and resilient farming systems in response to abrupt climate fluctuations and existing opportunities (Altieri and Koohafkan, 2008; Pandey et al., 2003). The micro-catchment and *in situ* RWHM techniques are more commonly applied than the macro-catchment techniques for supplemental irrigation on farm lands (Chapter 2). This may be explained by the lower complexity of the designs and lower establishment costs required by the micro-catchment and *in situ* techniques as compared to the macro-catchment systems. The only macro-catchment techniques that have been popular amongst the smallholder farmers are the traditional spate irrigation techniques in eastern Africa (Tesfai and Stroosnijder, 2001). Despite the possibility of improving the indigenous practices through scientific skills and experiences from elsewhere, the recent efforts of RWHM interventions focused more on the introduction of new techniques without sufficient engagement of the farmers (Chapter 2). However, the massive efforts to introduce new rainwater harvesting techniques has only resulted in meager successes and low levels of acceptance by the smallholder farmers (Abera, 2004; Mengistu and Desta, 2011; Spaan, 2003).

A review of field studies across the SSA revealed that rainwater harvesting techniques alone can improve grain yields by up to 56% while in combination with added fertilizer the grain yields can increase from 200 to 600% as compared to the traditional techniques (Chapter 2). The soil water content of the rooting zone can be improved by up to 30% due to the implementations of *in situ* and micro-catchment RWHM practices thus mitigating the adverse effects of dry spells. Although integrating rainwater harvesting with soil amendments is always imperative due to current poor fertility of most soils in drylands, grain yield gains vary depending on the patterns of seasonal rainfall. During years with well-distributed rainfall in the Sahel, RWHM techniques without addition of nutrients had little influence on crop yields while application of nutrients alone resulted in much higher grain yields (Zougmoré et al., 2003). Despite the beneficial effect of tied-ridges in years of near-normal (500–600 mm) rainfall in Tanzania, in wet years (700–900 mm) waterlogging effects had to be tackled through larger applications of fertilizers that enhance the water uptake capacity of maize (Jensen et al., 2003). Thus, appropriate seasonal weather forecasting would assist farmers to optimize their immediate decisions and tactically plan for response farming during the approaching seasons.

Previous experiences showed that transfer of best practices from one area to another should be applied judiciously due to inconsistent performance of RWHM techniques in response to different environmental and socioeconomic settings. Therefore, for an effective planning and development of rainwater harvesting techniques, it is imperative to make due considerations of prevailing determinants for crop production, local knowledge and opportunities. In the degraded lands of the Sahel region in Burkina Faso where soil degradation is also a crucial determinant for crop production, implementation of *zai pits* with compost and manure rehabilitated crusted desert soils thus improving water availability and fertility level of the soil simultaneously (Reij et al., 2009; Spaan, 2003). Short dry spells can be mitigated with *in situ* and micro-catchment RWHM practices. But other agro-meteorological determinants like short growing seasons, early cessation of the rainfall season or long dry spells could be aptly addressed through deficit or supplemental irrigation using rainwater storage ponds (Araya and Stroosnijder, 2011; Fox and Rockström, 2003). However, macro-catchment water harvesting techniques may not be applicable everywhere either due to unfavorable terrain conditions, or due to the lack of runoff inducing precipitation which does not allow to collect and store surface runoff. It is also imperative to explore the locally available opportunities such as rock fragments for stone mulching or bunds, manure for soil improvements or crop residues for surface mulching. Genetic enhancements that target early growth vigor to reduce evaporation and increase resistance to droughts could also add up to improvements in water productivity per unit of rainfall (Asfaw, 2011; Bennett, 2003; Bindraban, 1997; Molden et al., 2010). Overall, Chapter 2 implied that dryland agriculture can be improved and sustained through integrated interventions in water, soil and crop management techniques.

7.2 Linking drought vulnerability to trends in land-use and land management

The interplay between drought vulnerability and the changing trends in land-use and land management in the CRV drylands of Ethiopia was the topic of focus in Chapter 3. Although pastoral life has been the main livelihood strategy and even presumed to be a sustainable land-use system in many dryland regions, worldwide there has been an increasing conversion to mixed farming systems at the expense of woodlands and rangelands (Diouf and Lambin, 2001; Mortimore and Turner, 2005; Reenberg and Lund, 1998; Tsegaye et al., 2010). This study also indicated that dense acacia cover in the CRV of Ethiopia decreased from 42% in 1965 to 9% in 2010 while cultivated lands increased threefold (Chapter 3, Table 3.4). Thus, the question is: does drought vulnerability contribute to the on-going land-use conversion in such a way that mixed farming enables to cope better with recurrent drought than pastoral life? Based on the data generated in this thesis, the answer is ‘yes’ at least for the CRV drylands.

Long-term meteorological analyses implied that mixed farming systems were less vulnerable to severe droughts (once in seven years) than the pastoral way of life (once in four years) during the last three decades (Chapter 3). Drought years for livestock and crop production vary mainly because livestock keeping and crop production have different requirements of rainfall onsets. Apart from onset, long dry spells during the growing season can be the cause of severe or moderate droughts for crop production (Chapter 3, Table 3.6). While 50% of the drought years for livestock were good years for maize cultivation having above-normal rainfall amounts during the growing season, 38% of drought years for maize were good years for livestock. The findings of the meteorological analyses have been confirmed by accounts of local people who mentioned that mixed farming is better than pastoral life for coping with drought.

Another interesting insight of Chapter 3 is that the farmers of the CRV are not willing to continue land-use conversion until the woodlands and grasslands are completely gone, as it has been implied by the recently decreasing rate of conversion to cultivated lands (Table 3.4). This is contrary to other humid and dry sub-humid areas of Ethiopia where land cover change from native vegetation to crop cultivation continued until almost all the vegetation was gone (Dessie and Kleman, 2007; Zeleke and Hurni, 2001). The farmers of the CRV are well aware of the fact that crop cultivation alone cannot be a guarantee to cope with recurrent drought that affects crop production. Moreover, livestock rearing and maize cultivation complement each other - oxen are used to plough the land and crop residues can be used as fodder for the livestock during the extended dry seasons. Major purposes of the livestock are draught power, milk and related dairy products for household consumption, and income from sale particularly when crop production is a failure.

Therefore, the outcome of this study implied that addressing drought vulnerability of pastoral people should be taken as an important step towards mitigation of the on-going degradation of remnant woodlands and savannah in dryland regions. For the pastoral people, it is always difficult to restore the livestock that was lost by severe droughts, particularly when recovery phases are interrupted by new droughts (Angassa and Oba, 2007; Oba, 2001). The recent drought (2011) which put more than 12 million people under famine mainly in pastoral areas of eastern Africa (Ethiopia, Somalia and Kenya) has been caused by the failure of two consecutive rainfall seasons that caused a severe loss of livestock due to lack of recovery phases (FEWSNET, 2011). The vast drylands in the horn of Africa being a drought hotspot, land-use conversion from pastoral to mixed-farming system is likely to continue. Besides, climate change scenario simulations predict further increases in extreme events of drought that could destabilize human stability.

Although better flexibility and coping with drought is possible after shifting from pastoral to mixed farming, Chapter 3 further implied that the erratic nature of the rainfall, late onset of rainfall and high probability of dry spells are common phenomena causing agricultural water scarcity in the CRV of Ethiopia (Chapter 3, Figures 3.4 and 3.6). Hence, along with the shift from a pastoral to mixed-farming systems, farmers tried to adopt a range of improved land management techniques for in situ rainwater harvesting on farmlands (Chapter 3; Table 3.7). This is in line with the historical experience of coping with drought and climatic variability either through farm diversifications or adoption of better land management and rainwater harvesting techniques (Cooper et al., 2008; Flueret, 1986; Pandey et al., 2003).

7.3 Linking conventional tillage to rainfall partitioning

To get more insight in the effect of the widely applied conventional *Maresha* ploughing on rainfall partitioning for dryland agriculture, a field study was conducted on the soil water properties in response to conversion from acacia-based grasslands to cultivated lands. The impacts of long-term conventional tillage with the *Maresha* plough were also studied (Chapter 4). Due to V-shaped and incomplete ploughing by the traditional *Maresha* ard plough, farmers traditionally till the sandy loam soils 2 to 4 times before sowing of maize in the CRV. In the absence of appropriate use of soil amendments, this type of tillage causes excessive pulverization, poor soil structure and crust formation (Temesgen, 2007). Infiltration and evaporation are the two key soil water properties affecting inflow and outflow of water within the soil system respectively. Therefore, understanding the dynamics of these two processes in response to land-use conversion and long-term conventional tillage can give a good insight into the development of improved tillage and appropriate soil amendment techniques.

7.3.1 Infiltration

Infiltration rate in the surface soils increases significantly immediately after land-use conversion from acacia-based grasslands to cultivation (Chapter 4, Figure 4.4). However, there is a weak decreasing rate of infiltration with increase in the durations of cultivation on the soils from 2 to 35 years since land-use conversion. The lower infiltration rate on the soils of the acacia-based grasslands is explained by the significantly higher penetration resistance particularly in the top 8 cm soil layer of the acacia-based grasslands as compared to the cultivated soils (Chapter 4, Figure 4.7). The long-term trampling effect by the grazing animals causes compaction and higher penetration resistance of the soils in the acacia-based grasslands. Following land-use conversion from acacia-based grasslands to cultivation, the consecutive and cross-ploughing practice loosens the compacted surface soils thus enhancing the rate of infiltration. The weak decreasing rate of infiltration with increase in the durations of cultivation from 2 to 35 years since land-use conversion could not be fully explained by this study. Deterioration of the natural soil aggregates due to repeated tillage and the consequent slaking and particle rearrangement by raindrop impact causes soil crusting in sandy loam soils that in turn impede infiltration (Hoogmoed, 1999; Hoogmoed and Stroosnijder, 1984; Rockström et al., 1998). Although surface crusting is a prevailing problem in the sandy loams of the CRV (Chapter 4; Figure 4.1), the hypothesized effect of long-term tillage with the *Maresha* plough on soil crusting and the consequent reduction in infiltration requires further investigation. The reflection from this study is that long-term conventional tillage using the *Maresha* plough, where there is a maize mono-cropping system and no soil amendment techniques, may reduce the infiltration capacity of the sandy loam soils.

7.3.2 Soil evaporation

Soil evaporation was lowest from the acacia-based grasslands and highest from cultivated land with the longest duration of cultivation since land-use conversion (Chapter 4; Table 4.2). The statistically significant differences in soil evaporation were, however, observed only during the first two days after a rain event that satisfied the field capacity of the soils. According to Richie (1972), during the first stage of soil evaporation, the soil is sufficiently wet for the water to be transported to the surface at a rate at least equal to the evaporation potential. The lower rate of soil evaporation in the acacia-based grassland compared to the cultivated plots could be due to the modified micro-climate on the acacia-based grasslands by the shading effect of the acacia trees, albeit sparse. Steiner (1989) has also reported higher rates of soil evaporation during the non-limiting first stage from conventional tillage compared to no-till treatments. The higher rate of soil evaporation from cultivated land of longest durations could not be fully explained. The lower wetting zone immediately after rain events in crusted soils could cause higher evaporation (Bresler and Kemper, 1970). Hence, further investigation is required to better understand the hypothesized effect of long-term pulverization and deterioration of the natural aggregates on surface crusting that might enhance soil evaporation. The insight from this study is that the existing land management in the sandy loams of the CRV, characterized by continuous maize mono-cropping and repeated tillage each season by *Maresha* ploughing likely enhances soil evaporation immediately after rainfall and makes the crops suffer more from dry-spells.

7.3.3 The need for water conservation

The increase in soil evaporation and the gradual decrease in infiltration with increased duration of cultivation entails the poor rainfall partitioning effect of long-term conventional tillage with the *Maresha* plough along with the poor soil amendment practices in the dryland soils. Thus, improved water conservation through improved tillage and soil management techniques are imperative. So far, the local farmers are adopting and practicing land management techniques that enable moisture conservation. The *Dirdaro* furrow which is commonly used in the northern drylands of the country has also been introduced to the CRV in association with the adoption of line sowing of maize. These furrows are prepared with the traditional *Maresha* plough during sowing of maize after every two planting rows at an average interval of 50-54 cm across the slope (Chapter 3). The soil from the ridges is inverted to both sides of the planting rows hence covering the soil moisture around the maize root zone from evaporation while also trapping surface runoff in the furrow. Moreover, farmers traditionally apply manual hoeing, 1-2 times during the first three weeks mainly to break the surface crusts and improve infiltration. About 35-45 days after planting, the *Shilshalo* ridging is also practiced with the traditional *Maresha* ploughing on the previously prepared *Dirdaro* furrows mainly to break the surface crusting and enhance infiltration (Chapter 4, Figure 4.1).

The adoption of these techniques by the local farmers without any external technical and institutional support might infer the acceptability of *in situ* rainwater harvesting techniques due to their simplicity to fit within the existing farming system. Addressing the drawbacks of the conventional tillage and further introduction of better land management and soil amendment techniques could be instrumental for achieving improved rainwater use efficiency. The available farmyard manure in the mixed farming system of the CRV, which is not being used for any other purposes, can be aptly exploited based on proper optimization through field experimentation.

7.4 The role of tied-ridges and soil improvements: simulation with AquaCrop

Calibration and validation of the FAO's AquaCrop model was made based on field experimental data on a local maize variety. Thus water use efficiency and grain yields of the maize crop were simulated with tied-ridges and traditional tillage in response to different rainfall patterns and soil fertility levels (Chapter 5). The model simulation revealed that the effect of tied-ridges alone performed better than soil fertility improvements during below-average rainfall seasons. During above-average rainfall seasons, the combined applications of tied-ridges and soil fertility improvement was found very effective to substantially improve maize yield. This is because the excess water held in the tied-ridges can be best utilized due to the enhanced water uptake capacity of maize growing in the fertilized soils. Maize waterlogging problems were reported in association with the applications of tied-ridges during high rainfall seasons in fine loamy soils elsewhere (Jensen et al., 2003). In the CRV of Ethiopia, however, simulations based on long-term rainfall data revealed that waterlogging problems due to the application of tied-ridges on the sandy loam soils is less likely (Chapter 4, Figure 4.6). This may be also explained by the absence of long wet spells that could keep the soil water content near to saturation for consecutive days in the CRV. Depending on the seasonal rainfall patterns, the combined use of tied-ridges and optimum level of soil fertilizer doubles the rainwater use efficiency of maize. This is mainly due to the low fertility level (46%) of the shallow sandy loam soils. During a field experimentation in 2010, when rainfall was around average, the combined use of dry farmyard manure (4.5 Mg ha^{-1}) and tied-ridges increased maize yield by 47% while tied-ridges only increased maize yield by 26%.

Chapter 5 has also given insight into the expected effect of tied-ridges and soil fertility improvements in response to different times of sowing and rainfall distribution during the growing season. For an early-maturing maize (120 days), which is popular in the CRV, the best time of sowing is during the month of May. Hence, the water sensitive flowering stage will then be during July and August when there is lower probability of long dry spells (Chapter 3, Figure 3.6; Chapter 5, Figure 5.8). This is in line with what the local farmers normally do – they consider the month of May as the best time of sowing as long as it matches with a successful onset. Long-term simulation revealed that the effect of tied-ridges on yield improvements was higher for sowing in April than for sowing in May (Chapter 5, Figure 5.8).

Field experiments during the 2009 and 2010 growing seasons revealed that runoff was triggered with rainfall amounts of around 12 mm per day. The field observation revealed that 18-30% of the seasonal rainfall may be lost in the form of runoff. Given the fact that about 81% of the total rainfall during the growing season is explained by the sum of rainfall records with greater than 12 mm per day, the non-productive water flow through surface runoff is probably high. Thus, not only tied-ridges but also other types of rainwater harvesting techniques associated with runoff harvesting could be feasible, at least biophysically, in the CRV.

7.5 Towards a participatory planning of rainwater harvesting and management

Despite the possibility of enhancing the rich indigenous experiences through scientific knowledge and experiences from elsewhere, recent efforts of RWHM interventions in SSA focused on the introduction of new techniques without the full engagement of the farmers (Chapter 2). In Ethiopia, there have been extensive efforts to implement rainwater harvesting and management interventions for moisture-stressed and pastoralist areas, but with low level of farmers' participations at different phases of planning and implementations (Abera, 2004; Mengistu and Desta, 2011). Despite the huge investments nationwide, there have been only meagre successes with regards to adoption and wider dissemination of the externally introduced RWHM techniques. Therefore, in this study, a participatory rainwater harvesting and management planning approach has been proposed based on various research and development experiences (Biazin et al., 2011a; Lininger et al., 2011; WOCAT, 2007) and tested for the development of *in situ* rainwater harvesting in the CRV (Chapter 6).

The new planning approach enables not only to exploit the existing knowledge and opportunities, but also allows farmers to select and introduce acceptable practices in accordance with their socioeconomic and environmental settings. It starts by identifying the priority agro-meteorological and associated biophysical determinants of crop production which need to be addressed through appropriate rainwater harvesting techniques. New potential techniques that have been effective elsewhere are identified and illustrated to the farmers for possible modifications in accordance with the existing opportunities, and socioeconomic and biophysical settings. This is one of the most important and yet difficult steps in the new approach. Hence, based on an extensive review of different efforts, an outline of the most commonly applied in situ and micro-catchment RWHM techniques and their performances have been made available for development agents as part of this study (Chapter 6, Tables 6.7 and 6.8). However, expected crop yield gains due to the introduction of certain rainwater harvesting techniques to a given agro-meteorological and edaphic conditions cannot be availed only from secondary sources (Chapter 6). Hence, more scientific support is needed to enrich the database with appropriate model simulations that may replace the expensive field testing. The good performance of the FAO's AquaCrop model to simulate the expected benefits of tied-ridges in response to different rainfall patterns and fertility levels indicates that it is possible to build a database about the expected benefits of the different techniques in response to different rainfall and soil conditions based on simulations in different regions.

The application of this new approach in the CRV for in situ rainwater harvesting techniques implied that any effort on the introduction of new techniques needs to assess the existing tillage, hoeing and associated land management practices. The existing practice of *Dirdaro* furrowing has been taken as a basis to introduce and develop tied-ridges that can be practiced using the *Maresha*-modified ridger. Given the possibility of planning an integrated rainwater harvesting and soil improvement techniques with this new approach, tied-ridges in combination with soil amendments by manure has been found feasible and acceptable by the smallholder farmers. In light of this, the new approach is expected to complement the recent large-scale efforts of rainwater harvesting interventions for improved agricultural development in the vast drylands of Ethiopia.

7.6 Recommendations for further research

This study implied that land-use conversion from woodlands to cultivation and long-term tillage using the traditional *Maresha* plough in a maize-based mono-cropping system causes poor rainfall partitioning through reduced infiltration and enhanced soil evaporation from sandy loam soils. For a full picture of the effect of long-term *Maresha* ploughing on soil water properties, further studies are needed on the dynamics of soil aggregate stability, organic carbon dynamics, bulk density, and crust formation in response to different durations of cultivation after land-use conversion. Recent efforts to develop conservation farming strategies based on non-inversion tillage methods revealed promising effects on rainwater use efficiency in the smallholder rainfed farming system of semi-arid and sub-humid areas of East and Southern Africa (Rockström et al., 2009). The *Maresha*-modified tillage implements have also shown promising rainwater use and crop productivity performances in Ethiopia (Temesgen, 2007; Chapter 5). Since farmers know their unique situations on their farming systems, farmers' participatory research could be crucial in the future development of conservation farming and in situ rainwater harvesting efforts.

Farmyard manure is abundantly available to be exploited for improvement of the poor sandy loam soils in the CRV of Ethiopia. The combined use of tied-ridges and optimum level of farmyard manure showed positive responses on crop yields during a normal rainfall. Further on-farm experimentations are required to understand the effect of manure application on rainwater use efficiency and crop productivity in response to different tillage techniques and rainfall patterns. Moreover, incorporation of agroforestry trees such as *Faidherbia albida* enhanced crop production in West African drylands through soil improvements (Kho et al., 2001). The possibilities of similar developments with local and exotic agroforestry trees need further investigations in the Rift Valley drylands of Ethiopia.

Soil evaporation being an important cause of non-productive water flows in dryland rainfed systems, converting some of that water to transpiration requires better techniques (Rockström, 2003). Although crop residue mulching is effective for reduction of soil evaporation in dryland regions, crop residues are often needed for income generation, or fed to livestock during the dry season, which limits the availability of mulch material in drylands (Sterk et al., 2001; Stroosnijder, 2009). In arid and semi-arid regions of China, research has shown that plastic mulching can reduce soil evaporation from cereal fields by more than 30% (Deng et al., 2006). It is recommended that similar approaches be tested and developed in the vast drylands of Ethiopia.

This study implied that long dry spells after onset of the rainfall season could cause 30% of the droughts causing severe declines or total failure of maize in the CRV of Ethiopia. However, the failure or severe decline in crop yields due to long dry spells cannot be sufficiently addressed only by *in situ* rainwater harvesting techniques (Chapter 6). Having a high probability of medium and long dry spells (Chapter 3) and the erosive nature of rain events, macro-catchment rainwater harvesting techniques for supplemental irrigation may be promising. Field experimentations and model simulation studies elsewhere in sub-Saharan Africa indicated the potential of supplemental irrigation from macro-catchment water harvesting systems (Araya and Stroosnijder, 2011; Barron and Okwatch, 2005; Fox and Rockström, 2003; Kahinda et al., 2007). However, strategic research is required to determine how these techniques might be applied and adopted in the Rift Valley drylands of Ethiopia.

Upon proper calibration and validation, the FAO's AquaCrop model can be aptly used to explore the potential of various rainwater harvesting and management techniques. Hence, local calibration of the most important input parameters such as water productivity for different crops and cultivars and validation of the model are required for a reliable simulation. Thus, it can be used to assess the probability of crop failure and severe yield reductions due to agricultural water scarcity at regional and national scales.

7.7 Extension and policy recommendations

The interplay between drought vulnerability and the observed land-use conversion from pastoral life to mixed farming has been explained previously. Land-use conversion from pastoral to mixed farming at the expense of woodlands and native vegetation have been reported also in other parts of the vast Rift Valley drylands in Ethiopia (Dessie and Kleman, 2007; Tsegaye *et al*., 2010). Therefore, addressing drought vulnerability of pastoral people through proper policy directives should be considered as a crucial step to the efforts of mitigating further woodland and savannah degradation in the fragile drylands.

Rainwater harvesting and management cannot be a panacea for all problems in dryland agriculture. Instead, it should be considered as an integral component of production enhancement interventions for improved and sustained dryland agriculture. The current divided and isolated agricultural extension packages need to be revised in Ethiopia. This study implied that substantial yield gains are the results of combined rainwater harvesting and soil improvement techniques in the CRV drylands. Therefore, for an effective and sustainable agricultural development in the vast drylands of Ethiopia, agricultural extension packages should combine rainwater harvesting ideals with agronomic principles. Along with rainwater harvesting practices, soil fertility improvements, genetic enhancements and timeliness of farm operations have much to do with improved crop water use efficiency.

The higher popularity of indigenous RWHM techniques compared to introduced techniques implies that the technology has long been considered as a strategy for resilience to climatic variability and local opportunities. Although crop farming did not have a long-term experience in the CRV, farmers are adopting better land management techniques for in situ rainwater harvesting. In light of this, rainwater harvesting initiatives should start from existing knowledge, and identification of the socioeconomic and biophysical settings. There should be an enabling institutional set up to engage the farmers at all levels of planning and development of rainwater harvesting and management interventions thus the priority challenges of agricultural production can be identified, and the existing experiences and knowledge can be exploited.

7.9 Limitations of the study

Although this study gives insight into the promising effects of combining *in situ* rainwater harvesting with soil improvement techniques on rainwater use efficiency and productivity of maize, it has been limited to two years of field experimental data. A long-term field experiment could have enabled to understand the scenarios of combining tied-ridges and farmyard manure in response to different rainfall patterns (time of onset, distribution and amount) during the growing seasons. Moreover, long-term data could have enabled better validation of the FAO's AquaCrop model.

This study has been undertaken on a shallow sandy loam soil which restricts deep drainage. Therefore, it might be difficult to extrapolate the positive effect of tied-ridges for water conservation and promote in other drylands where sandy loam soils might be deep. Thus, field testing and model simulations should precede wider dissemination of tied-ridges.

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Summary

Summary

Agriculture is the mainstay of Ethiopian economy and yet it is the most volatile sector mainly due to its dependence on rainfed systems (close to 97% of the agricultural land is rainfed) and the seasonal shocks that are frequently observed. The seasonal and annual rainfalls are highly unpredictable and variable with the greatest risks of crop failure in the vast dry land masses of the country. Long dry spells, erratic rainfall, and excessive loss of rainwater through non-productive pathways (surface runoff, evaporation and deep drainage) contribute to water scarcity in rainfed agriculture. Apart from this, deteriorated dryland soils have low infiltration and water holding capacity, shallow depths and are sensitive to crusting. Therefore, to keep in pace with the demand for food for the burgeoning population, the Ethiopian drylands should be made more productive through appropriate rainwater harvesting and management techniques. There is the need to develop techniques that minimize the non-productive losses of rainwater and maximize the water uptake capacity of plants.

Chapter 2 presented an overview of the various rainwater harvesting and management techniques in sub-Saharan Africa, and synthesised the biophysical performances and socioeconomic implications of the most common practices. The sub-Saharan Africa is actually the birthplace of a range of indigenous rainwater harvesting and management (RWHM) techniques. The micro-catchment and *in situ* RWHM techniques are more commonly applied than the macro-catchment techniques for supplemental irrigation on farm lands. The only macro-catchment techniques that have been popular amongst the smallholder farmers are the traditional spate irrigation in eastern Africa. Depending on rainfall patterns and local soil characteristics, appropriate application of in-situ and micro-catchment techniques could improve the soil water content of the rooting zone by up to 30%. Smart combinations of rainwater harvesting and soil improvements enable to increase crop yields by 200-600% as compared to the traditional farming without them. Furthermore, following the implementation of rainwater harvesting techniques, the cereal-based smallholder farmers could shift to diversified crops, hence improving household food security, dietary status, and economic return. However, the efforts of introduction and dissemination of new techniques has resulted in meagre successes in the adoptions by the smallholder farmers in many countries.

Chapters 3 dealt with the interplay between drought vulnerability and the changing trends in land-use/cover and land management in the Central Rift Valley drylands of Ethiopia. Drought vulnerability analyses, GIS/remote sensing techniques, and surveying were employed. Given onset of the rainfall seasons (for both livestock farming and crop cultivation) and long dry-spells after onset (for crop cultivation) as the main perceived causes of drought, 50% of the drought years for livestock were good years for maize cultivation while 38% of drought years for maize were good years for livestock. Therefore, the pastoral way of life was vulnerable to severe drought once in seven years on average while mixed crop-livestock farming system was vulnerable to severe drought only once in twenty eight years. In association with the shift from a pastoral life to mixed-farming system, a range of improved land management techniques used for in situ rainwater harvesting on farmlands have been adopted. Over the last 5 decades, cultivated lands increased to threefold while the dense acacia coverage declined from 42% in 1965 to 9% in 2010. The observed land-use changes were driven by the interplay of recurrent drought, socioeconomic changes, institutional dynamics, better access to market and improved technologies such as early-maturing maize cultivars and better land management. This study implied that addressing drought vulnerability of the pastoral people should be taken as an important step towards mitigation of the on-going degradation of remnant woodlands and savannah lands.

Chapter 4 examined the effect of land-use conversion from woodlands to crop cultivation and long-term tillage with traditional *Maresha* plough on soil water properties. For thousands of years, tillage in Ethiopia has been practiced with oxen ploughing using the traditional *Maresha* ard plough where consecutive tillage operations are undertaken perpendicular to each other. Infiltration and soil evaporation

were measured following rainfalls that satisfied the field capacity of the soils from acacia-based grasslands and cultivated lands of different durations (2, 7, 22 and 35 years) since land-use conversions. Infiltration rate of the surface soil layer increases significantly immediately after conversion from acacia-based grasslands to cultivation although there is a weak decreasing trend in infiltration rate with increases in the duration of cultivation. Immediately after rainfall that satisfied field capacity of the soils, daily soil evaporation increased significantly with increases in the durations of cultivation. Therefore, it is implied that long-term *Maresha* cultivation along with the present soil management causes poor rainfall partitioning and makes the maize crop more susceptible to drought and dry-spells. The outcome of this study implied that improved soil management and appropriate tillage are needed to maximize rainwater use efficiency and achieve sustainable agricultural production in the CRV of Ethiopia.

Chapter 5 presented the role of the FAO’s AquaCrop model in simulating the effect of rainwater harvesting techniques in response to different rainfall patterns and soil fertility levels in the CRV of Ethiopia. Based on field calibration and validation of the model, rainwater use efficiency and grain yields of a local maize variety (Awassa BH 540) could be simulated according to tied-ridges and traditional tillage. The model simulation revealed that the effect of tied-ridges alone performed better than soil fertility improvements during below-average rainfall seasons. During above-average rainfall seasons, the combined use of tied-ridges and soil fertility improvement was found very effective to substantially improve maize yield. This is because the excess water held in the tied-ridges can be best utilized due to the enhanced water uptake capacity of maize growing in the fertilized soils. Although maize water logging problems were reported in association with the applications of tied-ridges during high rainfall seasons in loamy soils elsewhere, long-term simulations in the CRV of Ethiopia revealed that water logging implications of tied-ridges is less likely. This is mainly because the absence of long wet spells that could keep the soil water content near to saturation for consecutive days. Depending on the seasonal rainfall patterns, the combined use of tied-ridges and optimum level of soil fertilizer doubles the rainwater use efficiency of maize. A field experiment during a normal rainfall in 2010 revealed that the combined use of farmyard manure (4.5 Mg ha^{-1}) and tied-ridges increased maize yield by 47% while tied-ridges in isolation increased maize yield by 26%. Chapter 5 has also given insights into the expected effect of tied-ridges and soil fertility improvements in response to different times of sowing and rainfall distribution during the growing season. For an early-maturing maize (120 days), which is popular in the CRV, the best time of sowing is during the month of May. Hence, the water sensitive flowering stage will then be during July and August when there is lower probability of long dry spells. This is in line with what the local farmers normally do – they consider the month of May as the best time of sowing as long as it matches with a successful onset. Long-term simulation revealed that the effect of tied-ridges on yield improvements was higher for sowing in April than for sowing in May.

Chapter 6 presented about the new participatory rainwater harvesting and management planning approach that has been proposed based on various research and development experiences and tested for the development of *in situ* rainwater harvesting in the CRV. The rationale behind the need for the new approach was the meagre success in the adoption and wider dissemination of newly introduced techniques despite the extensive efforts of introduction and promotion for moisture-stressed and pastoral areas. Based on a review of various research and development experiences, the participatory RWHM planning approach was developed in such a way that merging of indigenous knowledge with experiences from elsewhere and scientific knowledge is possible for an appropriate development of rainwater harvesting techniques for improved and sustained agricultural production. The approach starts with investigation of the priority agro-meteorological determinants for crop production and identification of the existing knowledge and opportunities. The proposed approach also enables to plan an integrated rainwater harvesting and soil improvement techniques. The application of this new approach in the CRV implied that any effort on the introduction of new in situ rainwater harvesting techniques should assess existing tillage, hoeing and associated land management practices. The existing *Dirdaro* furrow system could be taken as a basis to introduce and develop tied-ridges using the *Maresha*-modified ridger. Overall, this approach may augment the recent efforts of dissemination of RWHM techniques for improved agricultural development in the vast drylands of Ethiopia. Further testing of the new approach for the development of micro-catchment and macro-catchment practices is recommended.

Overall, the outcome of this study indicated that although RWHM can make a significant contribution towards improved agricultural productivity in dryland regions, it cannot be a panacea for all problems of dryland agriculture. Given the poor fertility level of most dryland soils, RWHM should be considered as an integral component of production enhancement techniques such as soil amendments and related agronomic practices. Thus, the current divided and isolated agricultural extension packages need to be revised. Enabling institutional set up is required to engage the farmers at all levels of planning and development of appropriate RWHM interventions. Apart from this, scientific information is required through long-term field experiments and modelling the effect of rainwater harvesting in response to climate variability and change. Field evaluation and long-term scenario simulations must precede introduction of new techniques.

Samenvatting

Landbouw is de belangrijkste steunpilaar van de Ethiopische economie maar toch is het de meest kwetsbare sector door de afhankelijkheid van regengevoede systemen (tegen de 97% van de landbouwgebieden in regengevoede) en de seizoensschokken die regelmatig worden waargenomen. De hoeveelheid neerslag per seizoen en per jaar zijn hoogst onvoorspelbaar en variabel, met een groot risico op misoogst in de droge gebieden van het land. Lange droge perioden, onregelmatige regenval en buitenproportionele verliezen van regenwater via improductieve routes (oppervlakte afstroming, evaporatie en verliezen aan grondwater) dragen bij aan waterschaarste in regengevoede landbouw. Daarnaast hebben bodems in gedegradeerde droogtegebieden een lage infiltratie en water retentie capaciteit en zijn ze ondiep en gevoelig voor de vorming van een korst. Om de voedselbehoefte bij te kunnen houden voor de groeiende bevolking, moeten de droge gebieden in Ethiopië productiever gemaakt worden door gebruik te maken van juiste ‘wateroogst’ en managementtechnieken. Er is behoefte aan ontwikkeling van technieken die de niet-productieve verliezen van regenwater minimaliseren en de opname van wateropname van planten maximaliseren.

Hoofdstuk 2 laat een overzicht zien van verschillende regenwateroogst- en management technieken in Sub-Sahara Afrika en geeft een samenvatting van de biofysische werking en sociaaleconomische gevolgen van de meest gebruikte technieken. Sub-Sahara Afrika is het ontstaansgebied van verschillende inheemse regenwater oogst en management (ROM) technieken. De ministroomgebied en in-situ ROM technieken zijn wijder verspreid dan de macrostroomgebied technieken voor het toepassen op landbouwgebieden. De enige macrostroomgebied techniek die populair is bij kleinschalige boeren zijn de overstromingirrigatie in Oost-Afrika. Afhankelijk van regenvalpatronen en lokale bodemeigenschappen, kan correcte toepassing van in-situ en ministroomgebied technieken het vochtgehalte in de wortelzone met 30% doen toenemen. Slimme combinaties van regenwateroogst technieken en bodem verbeteringen kunnen gewas opbrengsten met 200-600% doen toenemen in vergelijking met traditionele landbouw zonder deze technieken. Tevens, na de toepassing van regenwateroogsttechnieken, kunnen de graangebaseerde kleinschalige boeren verschillende gewassen toepassen, en dus de voedselzekerheid van het huishouden, dieet en economische inkomsten verbeteren. Echter, de introductie en verspreiding van nieuwe technieken in magere successen in de acceptatie door kleinschalige boeren in veel landen.

Hoofdstuk 3 behandelt het verband tussen droogtegevoeligheid en veranderende trends in landgebruik/bedekking en landmanagement in de Centrale Rift Gebergte droogtegebieden in Ethiopië. Droogtegevoeligheidsanalyses, GIS/Remote Sensing technieken, en interviews werden gebruikt. In 50% van de jaren met droogte die invloed had op vee, was de oogst van maïs goed. In 38% van de jaren met slechte maïsoogst door droogte, was de opbrengst voor veebedrijven goed. Hierdoor liepen veehouders gemiddeld iedere zeven jaar het risico op ernstige droogte, dit terwijl gemengde gewas-vee boerenbedrijven gemiddeld iedere achtentwintig jaar het risico op ernstige droogte lopen. In combinatie met de verschuiving van een veehoudersbestaan naar een gemengd landbouw systeem zijn een aantal verschillende verbeterde land management technieken gebruikt voor in-situ regenwateroogsttechnieken op landbouwgebieden. Geurende de laatste 5 decennia is het oppervlak aan landbouwgrond verdriedubbeld, terwijl de dichtbegroeide acaciagebieden zijn afgenomen van 42% in 1965 naar 9% in 2010. De waargenomen landgebruikverandering worden veroorzaakt door een samenspel tussen terugkerende droogte, sociaaleconomische veranderingen, institutionele dynamiek, betere toegang tot verhandelcentra en verbeterde technieken zoals vroegrijpende maïsrassen en beter landmanagement. Deze studie impliceert dat bij het behandelen van droogte, de gevoeligheid van veehouders als belangrijke stap naar het laten afnemen van de overblijvende bos- en savannegebieden.

Hoofdstuk 4 onderzoekt het effect van landgebruikverandering van bosgebied naar akkers en lange-termijnploegen met de traditionele *Maresha* ploeg op bodemwater eigenschappen. Al duizenden jaren heeft het ploegen plaats gevonden met het gebruik van ossen en de traditionele *Maresha* ploeg waar opeenvolgende ploegactiviteiten loodrecht op elkaar plaats vonden. Infiltratie en bodemevaporatie werden gemeten na regenbuien die de bodem op veldcapaciteit brachten, zowel op de acacia-graslanden en gecultiveerde landen 2, 7, 22 en 35 jaar na landgebruiksverandering. Infiltratiesnelheid van de bovengrond nam significant toe na de transformatie van op acacia gebaseerd grasland naar landbouwgebied, ondanks dat er een zwakke afnemende trend in de infiltratiesnelheid is bij een toename in de duur van de cultivatie. Direct na een regenbui neemt de bodemevaporatie significant toe bij een toename van de duur van cultivatie. Hierdoor wordt geïmpliceerd dat de lange termijn *Maresha* cultivatie samen met het huidige bodemmanagement slechte regenvalverdeling veroorzaakt en het maïsgewas gevoelig maakt voor droogte en drogeperioden. De uitkomst van deze studie impliceert beter bodembeheer en geschikte ploegtechnieken benodigd zijn om het gebruik van regenwater te optimaliseren en een duurzame landbouwproductie te bewerkstelligen in het Centrale Rift Gebergte van Ethiopië.

Hoofdstuk 5 laat de rol van de FAO's AquaCrop model zin bij het modelleren van het effect van regenwateroogsttechnieken in relatie tot verschillende regenvalpatronen en bodemvruchtbaarheidniveaus in het Centrale Rift Gebergte van Ethiopië. Gebaseerd op veldcalibratie en -validatie van het model zijn regenwatergebruikefficiëntie en gewasopbrengsten van een lokale maïssoort (Awassa BH 540) gesimuleerd aan de hand van verbondenruggen en traditioneel ploegen. De modelsimulatie liet zien dat het gebruik van alleen verbondenruggen beter presteerde dan bodemvruchtbaarheidverbeteringen gedurende een benedengemiddeld regenval seizoen. Gedurende een bovengemiddeld regenvalseizoen, bleek de combinatie van verbondenruggen en bodemvruchtbaarheidverbeteringen zeer effectief in het substantieel verbeteren van maïsopbrengsten. Dit komt doordat het overtollige water dat word vastgehouden in de verbondenruggen gebruikt kan worden door de verbeterde wateropname van maïs die groeit in de vruchtbare bodems. Ondanks dat elders verzadigingsproblemen werden gerapporteerd samen met het toepassen van de verbondenruggen gedurende het sterke regenvalseizoen op kleiige bodems, laten lange-termijnsimulaties in het Centrale Rift Gebergte in Ethiopië zien dat waterverzadigingsproblemen minder waarschijnlijk zijn. Dit komt voornamelijk door de afwezigheid van lange natte perioden die de bodem voor opeenvolgende dagen op verzadigingsniveau kunnen houden. Afhankelijk van de seizoensregenvalpatronen, verdubbelt de combinatie van verbondenruggen en een optimaal niveau van bodem bemesters de regenwatergebruikefficiëntie van maïs. Een veldexperiment gedurende normale regenval in 2010 liet zien dat een combinatie van boerderijmest (4.5 Mg ha^{-1}) en verbondenruggen de maïsopbrengst met 47% deed toenemen terwijl het alleen toepassen van verbondenruggen de maïsopbrengst met 26% deed toenemen. Hoofdstuk 5 heeft ook inzicht gegeven in het verwachte effect van verbondenruggen en bodemvruchtbaarheidverbeteringen in reactie op verschillende zaaimomenten en regenvaldistributie gedurende het groeiseizoen. Voor een vroegrijpende maïssoort (120 dagen), welke populair is in het Centrale Rift Gebergte, is mei het beste zaaimoment. Zodoende ligt de watergevoelige bloeiperiode dan in juli en augustus, met een lagere kans op een periode van lange droogte. Dit komt overeen met wat lokale boeren gewoonlijk doen – ze beschouwen de maand mei als beste moment om te zaaien voor zolang het overeenkomt met een succesvolle voortzetting. Lange-termijnsimulatie laat zien dat het effect van verbonden ruggen op opbrengstverbeteringen groter was met april als zaaimaand in vergelijking tot mei als zaaimaand.

Hoofdstuk 6 laat de nieuwe participatieve regenwateroogst- en managementplanning benadering zien die is voorgesteld gebaseerd op verschillende onderzoek- en ontwikkelingervaringen zijn gebaseerd en getest voor de ontwikkeling van in-situ regenwateroogsttechnieken in het Centrale Rift Gebergte. De motivatie achter de behoefte voor de nieuwe benadering was het magere succes in de acceptatie en verspreiding van nieuw geïntroduceerde technieken ondanks uitvoerige pogingen van introductie en promotie van vochtschaarse en nomade gebieden. Gebaseerd op een review van verschillende onderzoek- en ontwikkelingservaringen, is de participatieve regenwateroogst- en managementplanning benadering zo ontwikkeld dat integratie van inheemse kennis met ervaringen van elders en wetenschappelijke kennis mogelijk is voor een juiste ontwikkeling van regenwateroogsttechnieken voor verbeterde en duurzame landbouw. De benadering begint met het onderzoeken van de agrarische-meteorologische parameters voor de gewasproductie en identificatie van bestaande kennis en mogelijkheden. De voorgestelde benadering maakt het tevens mogelijk om een geïntegreerde regenwateroogst- en bodemverbeteringstechniek te plannen. De toepassing van deze nieuwe benadering in het Centrale Rift Gebergte houdt in dat iedere inspanning voor de introductie van nieuwe in-situ regenwateroogsttechnieken de huidige ploeg, schoffel en bijbehorende landmanagement activiteiten geanalyseerd moeten worden. Het huidige *Dirdaro* kanaal system zou als basis genomen kunnen worden voor de introductie en ontwikkeling van verbondenruggen gebruik maken van de aangepaste *Maresha* ploeg. Over het algemeen kan deze benadering de recente pogingen voor de verspreiding van regenwateroogst- en managementtechnieken voor verbeterde landbouw ontwikkeling in de droogtegebieden van Ethiopië. Het verder testen van de nieuwe benadering voor de ontwikkeling van ministroomgebieden en macrostroomgebieden wordt aangeraden.

De uitkomsten van deze studie geven aan dat regenwateroogst- en managementtechnieken een significante bijdrage kunnen leveren aan een verbeterde landbouwopbrengst in droogtegebieden. Toch is het geen wondermiddel voor alle problemen van landbouw in droogtegebieden. Gegeven het feit dat de meeste droogtegebieden een bodem hebben met een lage vruchtbaarheid, moeten regenwateroogst- en managementtechnieken gezien worden als een integraal onderdeel van productie verbeterende technieken zoals bodemtoevoegingen en aanverwante agronomische activiteiten. Dus, de huidige verdeelde en geïsoleerde landbouw verbeteringspakketten moet worden herzien. Het mogelijk maken van institutionele set-up is benodigd om boeren te betrekken bij alle niveaus van planning en ontwikkeling van geschikte regenwateroogst- en managementinterventies. Daarnaast moet de wetenschappelijke kennis verbeterd worden door het doen van lange termijn veldexperimenten en het modelleren van het effect van het oogsten van regenwater in relatie tot klimaatverandering. Veldevaluatie en lange termijn scenariosimulaties moeten de introductie van nieuwe technieken opvolgen.

PE&RC PhD Education Certificate

With the educational activities listed below the PhD candidate has complied with the educational 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 (5.5 ECTS)

Rainwater harvesting for dryland agriculture in the Rift Valley of Ethiopia

Writing of project proposal (4.5 ECTS)

Rainwater harvesting for dryland agriculture in the Rift Valley of Ethiopia

Post-graduate courses (3.9 ECTS)

Advanced statistics; PE&RC (2008)
Long-term dynamics of food and human development; PE&RC / WGS (2008)

Laboratory training and working visits (2.5 ECTS)

Working visit to the demonstration fields of different rainwater harvesting techniques; Wondo Genet College of Forestry and Natural resources, Alage technical and Vocational training Center (2008)
A 3-days visit and training on meteorological instrument (automatic weather station, rain gauge, pan evaporimeter, etc.); Melkasa Agricultural Research Center in Ethiopia (2008)

Deficiency, refresh, brush-up courses (4.2 ECTS)

Physical aspects of land management (2007)
Facilitating interactive processes (2007)
Basic statistics (2008)

Competence strengthening / skills courses (2.4 ECTS)

Scientific publishing; WGS (2007)
Career assessment; WGS (2011)
Techniques for writing and presenting a scientific paper (TWP); WGS (2011)
Information literacy including EndNote introduction (ILP); WGS (2011)

PE&RC annual meetings, seminars and the PE&RC weekend (0.9 ECTS)

PE&RC Meeting (2007)
Food security, water and forests (2011)
PE&RC Day (2011)

Discussion groups / local seminars / other scientific meetings (4.6 ECTS)

Annual soil science society of Ethiopia meeting (2009)
Interdisciplinary action research meetings at Wondo Genet College of Forestry and Natural Resources (2009, 2010)
Annual research reviews and seminars at Wondo Genet College of Forestry (2009, 2010, 2011)

International symposia, workshops and conferences (4.7 ECTS)

International conference on interdisciplinary action research for natural resources conservation in Ethiopia, Wondo Genet (2009)
International conference organized by the Netherlands Center for River Research (NCR), Delft (2011)
International Wageningen conference for applied soil science (2011)

Lecturing / supervision of practical's / tutorials (3 ECTS)

Rainwater harvesting technology; 68 days (2009)
Rainwater harvesting technology; 80 days (2010)

Curriculum vitae and author's publications

Birhanu Biazin Temesgen was born on September 16, 1975 in Gojjam, Ethiopia. He finished his secondary education from Motta in 1992. Birhanu has obtained his BSc degree in Forestry with great distinction being awarded a gold medal from Wondo Genet College of Forestry and Natural Resources in 1999. During August 1999 - August 2000, he has served as a graduate assistant in the same college. In September 2000, he got a Wageningen University fellowship for the Master program on Land and Water Management and specialised on soil and water conservation. Between 2002 and 2007, he has been involved in lecturing and research activities at Wondo Genet College of Forestry and Natural Resources. He has been teaching undergraduate courses like rainwater harvesting technology, erosion and soil conservation and integrated watershed management.

As he became more interested about rainwater harvesting and management development, he attended a short-term training entitled on "Planning and designing of rainwater harvesting technologies for sustainable agriculture" in Gansu province of China during August – October, 2005. He was a team leader for the rainwater harvesting research project under the "Development-Oriented Interdisciplinary Thematic Action Research" program that was funded by SIDA and monitored by Wondo Genet College during 2005-2007. In September 2007, he has got a Wageningen University Sandwich PhD fellowship at the Land Degradation and Development Group. His PhD research focused on participatory development of in-situ rainwater harvesting techniques in the Central Rift Valley Drylands of Ethiopia. He was awarded with additional funding from IFS and SIDA-Wondo Genet for his field research. During this period, he was also lecturing the course Rainwater Harvesting Technology for undergraduate students in Wondo Genet College. He has published a number of peer reviewed articles and made a number of oral and poster presentations in several international meetings. Birhanu is member of the International Soil Tillage Research Organisation (ISTRO).

Birhanu Biazin married Elizabeth Berhanu in January 2010 and has one child. He would like to continue in teaching and research about rainwater harvesting and drought adaptation strategies.
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Publications

Journal articles

Biazin, B., Stroosnijder, L., Temesgen, M., Abdulkedir, A., Sterk, G., 2011. The effect of long-term *Maresha* ploughing on soil physical properties in the Central Rift Valley of Ethiopia. Soil and Tillage Research 111, 115-122.

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