Exploring the potential of soil and water conservation as an adaptation strategy to climate change

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Summary

Developing countries which rely on agricultural production for survival are vulnerable to the negative impacts of climate change. An increase in droughts, floods and other extreme events in Africa are likely to have an impact on agricultural production and food security. The Research Program on Climate Change, Agriculture and Food Security (CCAFS), explores for methods to overcome the threats to agriculture and food security in a changing climate by searching for possibilities to help the vulnerable communities to adapt to climate change(CGIAR 2014). This is done by for instance, promoting adaptation strategies towards climate change. Soil and water conservation (SWC) are examples of such strategies. SWC aim to alleviate growing water shortages, worsening soil conditions, droughts and desertification. These strategies are generally low-cost interventions, however, they can be still too risky for very low-income households.

The positive effects of SWC strategies can often only be observed after a long time of managing. In this study, the effect of SWC as an adaptation strategy to climate change has been studied in one of the CCAFS study sites in Kenya. The study area was located in Makueni. In this area farmers have been managing under SWC strategies for a long time. This opened opportunities to study the long-term effects of SWC strategies on soil conditions. Fieldwork is done in order to find if the SWC strategies have an effect on soil conditions, by studying the soil properties. A crop-growth simulation model is used to find if these possible effects on soil conditions result in higher water-limited yields for maize under current climate conditions. The use of a crop-growth simulation model opened opportunities to study if SWC strategies can be used as an adaptation strategy towards climate change, by simulation different climate scenarios. The results of this study can confirm if the SWC strategies as promoted by CCAFS can indeed contribute as an adaptation towards climate change.

The main SWC strategies in this area are applying terraces and intercropping. The fields where SWC strategies were applied, were paired up with fields were no SWC strategies were applied. These paired fields were sampled and analysed on different soil properties. The soil properties that were analysed in order to study the effects of SWC were nitrate, pH and soil moisture. The results of the analysis for the soil properties of the paired fields were used to study whether the SWC strategies had an effect on the current water-limited maize yields, under dry, wet and average climate conditions. If the strategies had an effect on the simulation of future maize yields was studied by using four different climate scenarios for 2050. This is done by using the crop-growth simulation model WOFOST. This model uses soil data, weather data en crop characteristics as input to estimate the yields per growing season.

Higher contents of nitrate levels were found in the soils for the intercropping fields. The soil moisture was higher on the terraced fields. Terracing also resulted in an increase of water-limited yields in a dry year. It also resulted in higher water-limited yields under different climate scenarios. This implies that terracing is not only a great potential as adaptation strategy for climate change but also increases yields under current climate conditions. Although higher nitrate levels were found in the intercropping fields, did this not result in an increase of water-limited yields. For both current climate conditions as well as future climate scenarios, yields did not increase by intercropping.

Applying SWC strategies as promoted by CCAFS indeed improves soil conditions and terracing contributes as an adaptation towards climate change. Therefore continuing with stimulating farmers to apply such strategies –as done by CCAFS- can decrease threats to agriculture and food security in a changing climate. Increased water-limited yields by applying terraces makes farmers less vulnerable towards climate change and more food secure. Applying intercropping as SWC strategy likely has positive effects as well. However, the nutrient-limited yields should be evaluated in order to confirm this.

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1. Introduction

Awareness of climate change and its long-term impact on both our planet and the human existence have intensively increased the concerns of scientists, policymakers and the general public (IPCC, 2001). Developing countries which rely on agricultural production for survival are vulnerable to the negative impacts of climate change (Kates, 2000). An increase in droughts, floods and other extreme events in Africa are likely to have an impact on agricultural production and food security. Crop production will become more difficult in some regions, especially where climate variability plays an important role in determining productivity such as in areas where the food is grown as rain fed annual crops. Changes in precipitation patterns increases the chance of crop failure and the long-run production declines (Slingo et al., 2005).

Multiple research programs are focusing on building resilience towards climate change in the agricultural sector, such as the Global Yield Gap Atlas (GYGA) project and The Research Program on Climate Change, Agriculture and Food Security (CCAFS). For example, CCAFS explores for methods to overcome the threats to agriculture and food security in a changing climate by searching for possibilities to help the vulnerable communities to adapt to climate change (CGIAR, 2014). Developing conservation agriculture is one of their key challenges in order to achieve food security for smallholder farmers under a changing climate. This is done for instance, by promoting adaptation strategies towards climate change. These strategies aim to minimize harm or exploit beneficial opportunities as response to climate change by adjusting natural or human systems (IPCC, 2011). Soil and water conservation (SWC) are examples of such strategies (Adimo et al., 2012). SWC strategies have been suggested as strategy to alleviate growing water shortages, worsening soil conditions, droughts and desertification (Kurukulasuriya et al., 2013). These strategies are generally low-cost interventions, however, they can be still too risky for very low-income households (Dercon, 2004).

Kenya is characteristic of many countries in Africa with high levels of low-income households and food insecurity. The population often depend on rainfed agriculture for their survival and are likely to be the most affected due to climate change because of changes in rainfall patterns. Although future changes in rainfall patterns are insecure, yield declines for most important rainfed crops are expected (Nelson et al., 2009). The application of SWC strategies might therefore be unavoidable in this area.

The positive effects of SWC strategies can often only be observed after a long time of managing. In this study, the effect of SWC as an adaptation strategy to climate change has been studied in one of the CCAFS study sites in Kenya. The study area was located in Makueni. In this area farmers have been managing under SWC strategies for a long time (Förch et al., 2013). This opened opportunities to study the long-term effects of SWC strategies on soil conditions. A crop-growth simulation model is used to find if these possible effects on soil conditions results in higher water-limited yields for maize, which is the most important staple crop in the area (Förch et al., 2013). The use of a crop-growth simulation model opened opportunities to study if SWC strategies can be used as an adaptation strategy towards climate change, by simulation different climate scenarios. The results of this study can confirm if the SWC strategies as promoted by CCAFS can indeed contribute as an adaptation towards climate change. If SWC contributes as an adaptation to climate change, it can stimulate farmers to apply this strategy.
In order to study the potential of SWC as an adaptation strategy to climate change, the following is analysed;

- The differences in soil properties by applying SWC strategies,
- The effect of SWC strategies on water-limited crop yields, and
- The effect of climate scenarios on water-limited crop yields.

2. Materials and methods

2.1 Overview

In order to study the effect of SWC strategies on soil properties and how these changes affect water-limited yields, different steps are taken. An overview of these steps are represented in Figure 1. In this chapter, a description is given in how this is done.

First, a detailed description of the SWC strategies found in the study area are described. These were found by conducting a combination of fieldwork as well as household surveys. The fields where SWC strategies were applied, were paired up with fields were no SWC strategies were applied. These paired fields were sampled and analysed on different soil properties in the second step. This type of research is done because the effect of SWC on soil properties are often only measurable after multiple years of managing. In the third step, the results of the analysis for the soil properties of the paired fields were used to study whether SWC have an effect on water-limited crop yields. This is done by using a crop-growth simulation model. The model is run for both current climate conditions as well as for future climate conditions. The use of a model in this study opened opportunities to simulate future yields by using different climate scenarios established for the year 2050. This is done in order to study if SWC can contributes as an adaptation strategy to climate change.

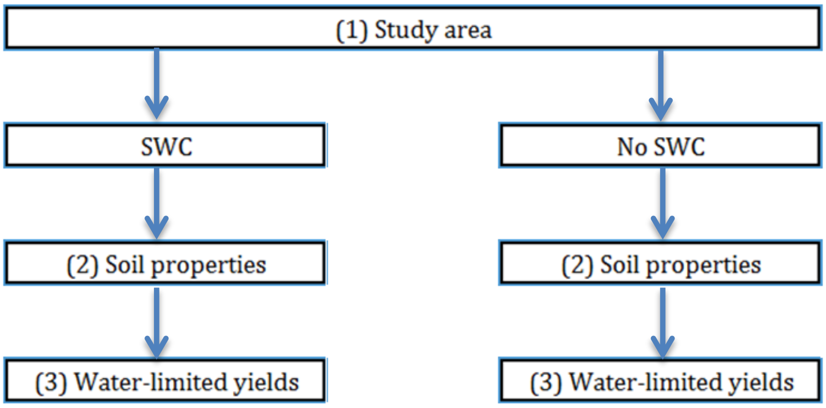

Figure 1. Flowchart of the methods. The numbers resemble the steps taken in order to study the effect of SWC on soil properties and how these changes affect water-limited yields.

2.2 Study area

Location

This research in conducted in one of the CCAFS study sites in Kenya. The study area is found in the Makueni county, which is found in the southeast of Kenya. The CCAFS site is identified by a squared area of 10 x 10 km (1.809- 1.900˚ S and 37.724- 37.630˚ E, Figure 2). One of the criteria for this specific site for CCAFS is the challenge of meeting the food demands with food supply (Förch et al., 2013). Makueni District is generally a food deficit area, with a 66% headcount poverty rate.

The main SWC practices in the area include terracing, intercropping, manure application and crop rotations. A detailed description of these strategies can be found in chapter 2.3.

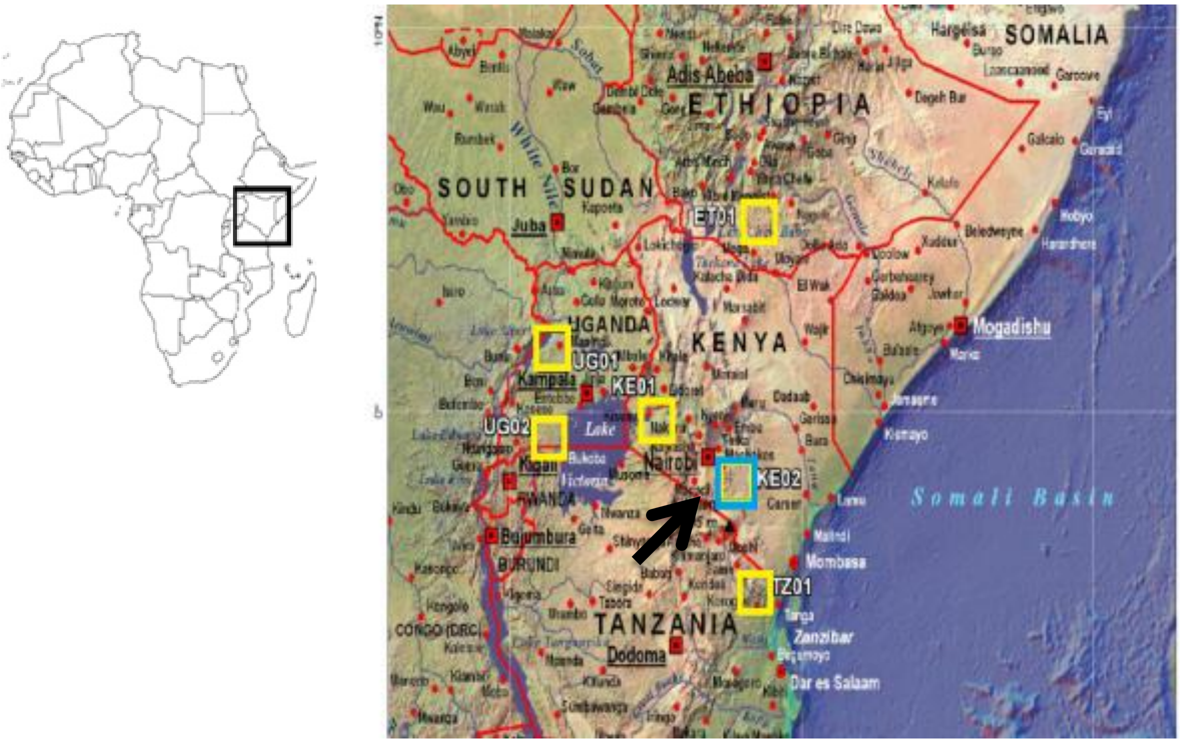

Figure 2. CCAFS locations in Eastern Africa. The study area is located in one of the CCAFS sites in the eastern province of Kenya. The CCAFS site of this study is rimmed in blue.

Climate

The semi-arid climate in the area has daily temperature varying from 14.5 °C up to 31.8°C and a high variability in annual and seasonal rainfall. Mean monthly variation in temperature and rainfall is displayed in Figure 3 and annual variation in rainfall is displayed in Figure 4. The graphs are derived from data of Kambi Ya Mawe meteorological station, which is in the middle of the study area. The mean annual rainfall at the Kambi Ya Mawe meteorological station is 470.9 mm, distributed over a long (March-May) and a short (October-December) raining season, separated by a distinct dry season (Figure 4). The short rainy season is generally considered more reliable than the long rainy season and receives slightly higher rainfall than the long rainy season (Förch et al. 2013). The average monthly maximum temperature varies between 28.8°C and 32.5°C, the minimum varies between 14.6°C and 19°C.

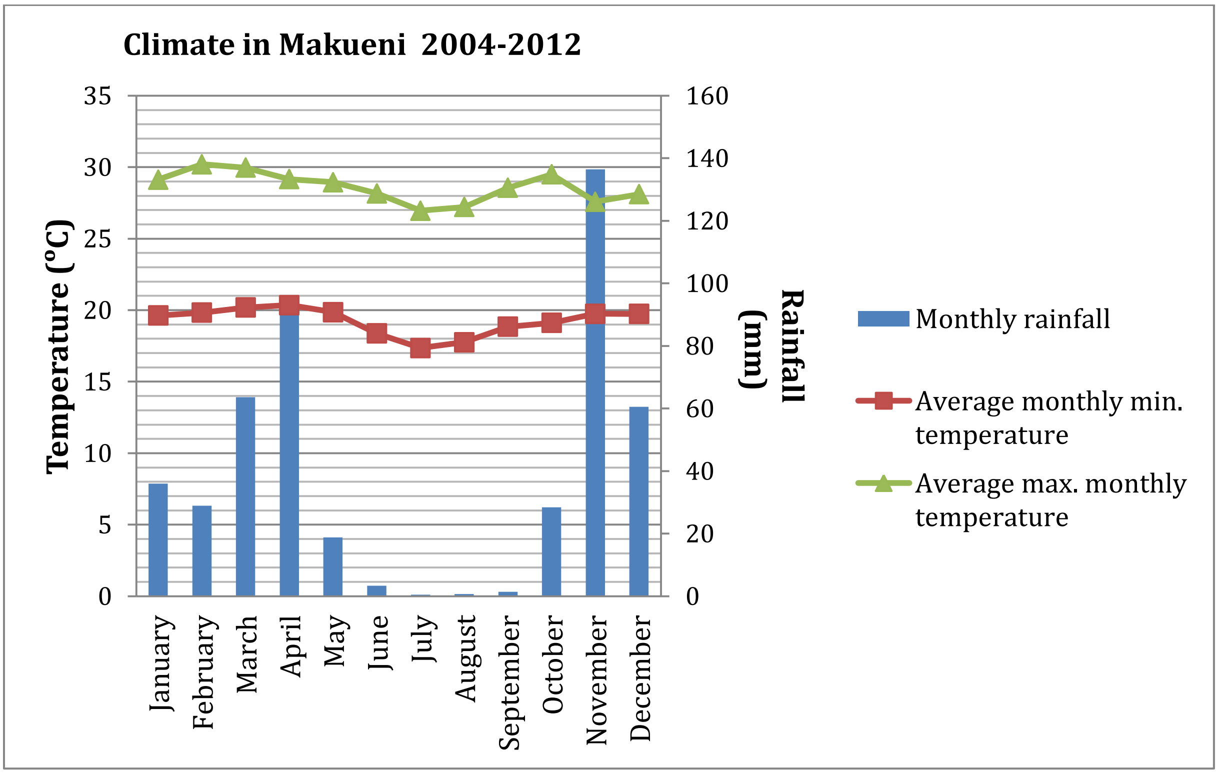

Figure 3. Mean monthly maximum and minimum temperature and mean monthly rainfall. Derived from daily weather data of Kambi Ya Mawe meteorological station, from 2004-2012.

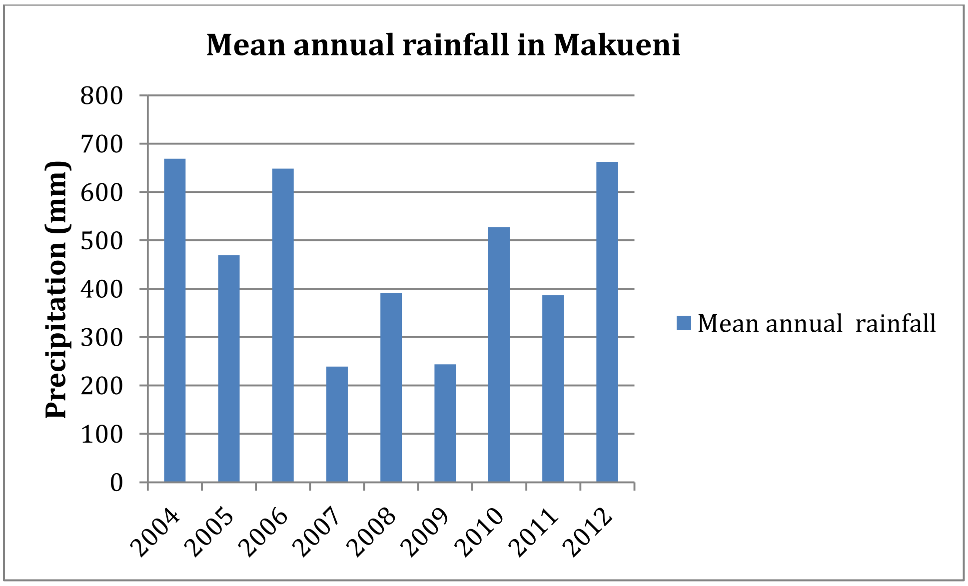

Figure 4. Annual rainfall. Calculated from daily weather data from Kambi Ya Mawe meteorological station, from 2004-2012.

Geology

The area is mostly covered by the Basement System from the Precambrian. Originally, this system consisted solely of sedimentary rocks. In a later stage intrusions with igneous rocks took place. An east-west compression folded the original sediments and depressed them into the lower parts of the Earth's crust. This resulted in metamorphoses and granitizing of the rocks. A wide variety of gneisses and schist are now found in the study area, including amphibolites, quartzites and biotite granitoid gneisses (Mora-Vallejo et al. 2008).

Soils

Most of the soils in the area are deep to very deep, with textures ranging from sandy clay loam to sandy clay (Mora-Vallejo et al., 2008). They generally have a porous massive structure with moderate to high water holding capacity and good drainage. Erosion can take place at the beginning of the rainy season. Soil fertility is very poor with low SOC, nitrogen and phosphorus. The soils are classified as typic Eutrustox (Ferrasol, in the FAO classification), ultic Haplustalfs (Lixisol or Luvisol), oxic Paleustults (Acrisol) and rhodic Paleustalfs (Lixisol or Luvisol) following the Soil Taxonomy (OSD, 1998). The Typic Eutrustox are dark reddish brown to dark red and can be found in the uplands. Here, the parent material is mainly quartzite. This type of soil is located in the densely populated areas where the most of the fields are terraced (Claessens et al, 2012). The rhodic Paleustalfs can be found in the lowlands and at the west border of the study area. The parent material is mainly biotitegneisses. The soils are red to dark reddish bown in colour. The southern part of the area mainly consist of ultic Haplustalfs and oxic Paleurstults, which are dark brown to yellowish brown in colour, with biotite gneisses and undifferentiated basement systems rocks (Mora-Vallejo et al., 2008). In Table 1, the soil classifications with their average soil properties are shown.

Table 1.Soil properties of the different soil classes found in Makueni (Onduru et al.,2001).

Soils classes in Makueni	Depth	Water holding capacity (vol.%)	Bulk density (kg/l)	SOC (%)	Clay (%)	pH	CEC (meq/100g)
Typic Eutrustox	0-30 cm	8.3	1.32	1.16	35	6.9	9.3
Rhodic Paleustalfs	0-30 cm	9.2	1.43	0.53	17	6.2	9
Ultic Haplustalf	0-30 cm	13.3	1.25	0.87	46	6.5	9.8
Oxic Paleustults	0-30 cm	19.1	1.36	0.44	53	6.4	11.8

Land use

The majority of the population in Makueni (884,527 (2009 census)) are smallholder farmers (Förch et al. 2013). In general, the farm households own 1.5 and 6 ha, of which 1.5-3.5 is cultivated and mainly terraced (Onduru et al., 2001; De Jager et al., 2005). After severe land degradation farmers were forced to build erosion control structures in the 1930s (Tiffen et al., 1995; De Jager et al., 2005). Nowadays, the majority of the farmers voluntary maintain these structures (de Jager, 2007).

The most important staple crop is maize, followed by large varieties of crops such as beans, pigeon pea, cow pea, green grams and sorghum. Fruit trees and vegetables are also grown, but in a smaller extent. The growing seasons are defined by the raining seasons; the long raining season (March-May) and the short raining season (October-December). For all crops the yields are generally low (around 1597 kg/ha per growing season for maize), mainly due to shortage of nutrient- and water supply to the plants (Claessens et al. 2012). Intercropping is the main farming activity; farmers combine maize often with either pigeon pea and/or beans simultaneously (Onduru et al., 2001; De Jager et al. 2005). Most farms have some livestock (cows and/or goats) which are kept for manure, dairy products, cultivating land and provision of water. The amount of manure is often not enough to cover the entire field, therefore farmers often apply manure rotation; each growing season, another part of the field is applied with manure rather than completely covering the entire field. Chemical fertilizer is rarely applied due to relatively high prices (Onduru, 2001; De Jager et al, 2005; Mora-Vallejo et al. 2008).

2.3 Soil water conservation

The main current SWC strategies found in the study area are terracing, intercropping, manure application and crop rotation (Förch et al. 2013). For this research, only the effect of terracing and intercropping have been studied. The effect of crop rotation is not studied, because there is no insight in which crops have been growing on certain places in previous growing seasons. The effect of manure application has not been studied because there is no insight in the amount of manure that has been applied on the fields as well as the location and time where it was applied.

2.3.1 Intercropping

Intercropping is the main farming activity in the study area. Maize is often combined with pigeon pea and beans (Onduru et al., 2001). Advantages of intercropping are for example: maximizing the use of environmental resources and minimizing risk of total crop failures as well as nitrogen nutrition to the soil through biological nitrogen fixation. It also reduces the need of industrial fertilizers (Carlsson, 2003). Biological nitrogen fixation is, next to plant photosynthesis, probably the most important biochemical reaction for life on earth (Brady and Weil, 2004). Certain organisms convert the inert dinitrogen gas of the atmosphere (N_2) to nitrogen–containing organic compounds that become available to all forms of life (Brady and Weil, 2004). Different N-fixing systems exists; symbiotic fixation with legumes, symbiotic fixation with non-legumes and non-symbiotic nitrogen fixation. Legumes are often associated with nitrogen-fixing organisms and include valuable food such as peas and beans. The biggest source of N fixation is formed by the symbiosis of legumes and bacteria of the genera rhizobium (e.g. for beans, chickpea and green grams) and bradyrhizobium (e.g. cowpea and pigeon pea) in agricultural soils (Brady and Weil, 2004). Typical levels of nitrogen fixation for different legumes are shown in Table 2.

The organisms make the formation of root nodules where the nitrogen fixation occurs. The host plant supplies the bacteria with carbohydrates for energy in exchange for fixed nitrogen compounds. Over time, the presence of legumes can significantly increase the nitrogen content of the soil and can give benefits to non-fixing species grown in associations with the legumes.

In this study only the effect of symbiotic fixation with legumes will be studied because other fixing systems are either not relevant due to the absent of these fixing crops on the agricultural fields or the assumed negligible contribution of N addition in the soil. The claim that the presence of legumes increases the nitrogen content of the soil and give benefits to the non-fixing species over time, will be tested in this study. The addition of N of the soil, likely leads to higher fertility and therefore an increase in crop-production is expected. Additionally, the lack of manure and fertilizer in the study area (Förch et al. 2013), makes this type of conservation practices highly attractive. With a higher crop-production, higher inputs of organic matter is expected and therefore relatively a higher soil moisture (Hoffland et al. 2013).

Table 2. Typical levels of nitrogen fixation by legumes (Brady and Weil 2004)

Symbiotic fixation with legumes	*Associated organism*	*Typical levels of nitrogen fixation, kg N/ha/yr*
Bean	Bacteria (Rhizobium)	30-50
Cowpea	Bacteria (Bradyrhizobium)	50-100
Pigeon Pea	Bacteria (Bradyrhizobium)	150-280

2.3.2 Terracing

The type of terraces found in the study area consists of a small dam and a ditch, which is called as Fanya Juu (Figure 5). Fanya Juu is the Swahili expression for 'throw uphill'. With on-going soil erosion, bench terraces form slowly (Figure 6). Level terraces can develop within seven years (Hudson, 1988). This results in a decrease in erosion and runoff. Crop production can stabilize or increase over time (Herweg and Ludi, 1999). Terraces need maintenance for soil moisture conservation which is crucial for crop production in many semi-arid areas such as Kenya. Additionally, it prevents nutrient losses due to erosion. An increase in crop production leads to an increased build-up of organic matter (SOM) and therefore higher fertility of the soil.

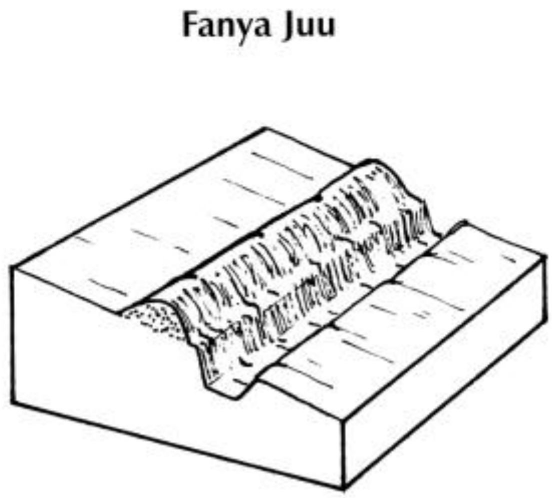

Figure 5. Cross section of a Fanya Juu terrace (Herweg and Ludi)

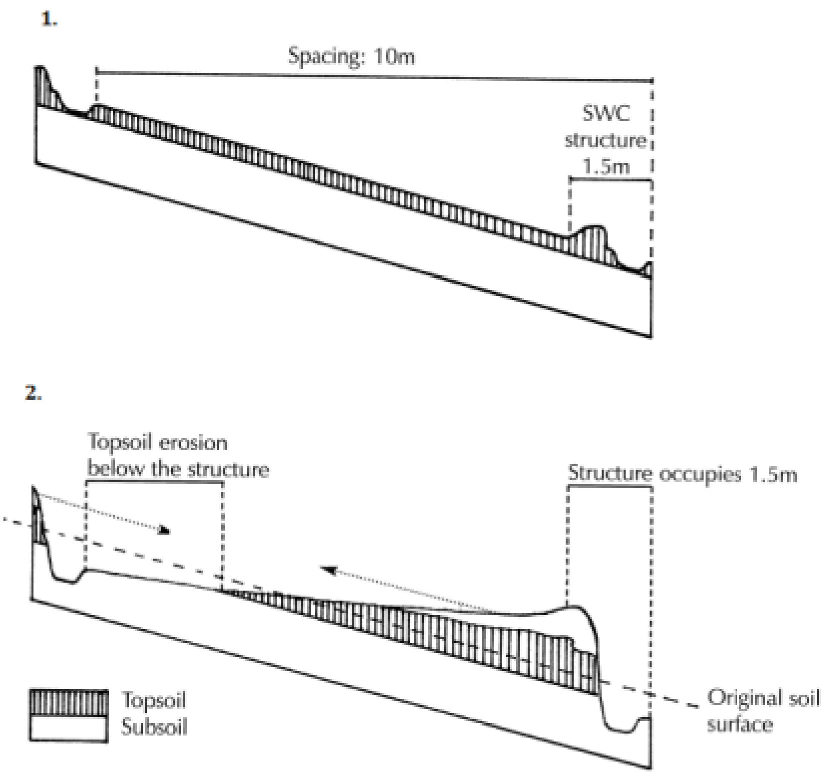

Figure 6. (1). Situation prior to the terrace levelled development. (2) steady situation after development (Herweg and Ludi 1999).

2.4 Crop-growth simulation model

To study if the applied SWC not only have an effect on soil properties but also on water-limited yields, a crop-growth simulation model is used. The model that is used for this study is WOFOST World Food Studies, version 2.2.1, 2013). WOFOST is a simulation model for the quantitative analysis of the production and growth of annual field crops (van Ittersum et al., 2012). With this model, the attainable crop production, biomass, water use etc. can be calculated for a certain location, based on the inputs (1) soil properties, (2) crop phenology and (3) weather conditions.

The water-limited yield is defined as the production situation where the growth rate is limited by shortage of water during at least a part of the growing period (Wu et al. 2006). For the water-limited yields, WOFOST keeps track of a daily water balance taking into account the water that is entering and leaving the rooting zone which depends on the weather conditions, the field capacities and the non- infiltration fractions. The non-infiltration fractions (runoff) are taken into account by calculating the fraction of rainfall that does not infiltrate into the soil, depending on the slopes of the field and the drainage class of the soils. The water that does not end up as runoff leaves the rooting zone by crop uptake -which results in transpiration-, percolation or soil evaporation. If the water supply is not optimal, the transpiration rate is reduced which also reduces the photosynthesis rate proportionally. A decrease in photosynthesis then results in an reduced growth and therefore yield. Severe droughts can result in crop failure (Wu et al., 2006).

2.5 Climate change

The model is run for both current climate conditions as well as for future climate conditions. The use of a model in this study opened opportunities to simulate future yields by using different climate scenarios established for the year 2050. These climate scenarios are derived from the Intergovernmental Panel on Climate Change report (IPCC, 2011). In Appendix I, graphs are shown with relative changes in temperature and precipitation predicted in East Africa, derived from the IPCC. The scenarios are based on four Representative Concentration Pathways (RCPs).

The RCPs are four greenhouse gas concentrations trajectories often used for climate modelling. They describe four possible climate futures, all of which are considered possible depending on how much greenhouse gases are emitted in the years to come. The four RCPs are: RCP2.6, RCP4.5, RCP6.0, and RCP8.5, ranging from the lowest emission- to the highest emission scenario. How these RCPs affect future climate, is estimated by General Circulation Models (GCM, Worldclim, 2014). Multiple GCMs exists, but for this study we used the Climate System Models of Beijing Climate Center (BCC-CSM1-1), in order to create site specific climate conditions for 2050 for our study area. This GCM is widely used for climate research (Xin et al., 2013) and is one of the few models which offers a complete data set needed for this study. This dataset is derived from Worldclim (Version 1.4). Worldclim (Worldclim, 2014) has translated the four RCPs into sets of global climate layers with different spatial resolutions (Hijmans et al. 2005).

2.6 Sampling strategy

2.6.1 Soil water conservation in the study area

To get insight in the SWC applied in the study area, agricultural fields were visited. Fields were visited randomly to get insight in the amount of intercropping and mono cropping fields. For the terraced/non-terraced fields this was not possible. The majority of the study area has terraced fields and therefore one has to search for the non-terraced fields.

2.6.2 Paired observations

In order to observe differences in soil properties by applying SWC strategies, paired observations are carried out. The SWC strategies taken into account are terracing and intercropping. Therefore, the two types of pairs are: (1) terraced/non-terraced and (2) intercropping/mono cropping. To find these fields, agricultural fields were visited and a combination of household surveys and field observations were conducted to select fields based on several criteria. The criteria for composing the pairs was that pairs should be more or less the same in soil texture, slope (measured with a clinometer), period of farming and management practices as manure application and crop rotation. Differences in soil texture, management etc. can have different effects on soil properties. Field observations were performed in order to find the mono cropping/intercropping and terraced/non-terraced fields. Household surveys were performed in order to get insight in the management of the field.

Farmers that were managing their farms not longer than two growing seasons were left out, based on the assumption that practices shorter than two growing seasons would not have an effect on soil properties. The farmers that did not apply intercropping currently and previous seasons were classified as mono cropping. If the terraces were less than two years old, they were also left out. The visited agricultural fields were also classified by terrace types (terraced/no-terrace/ridges). Fields with a slope bigger than five percent without ridges or terraces were classified as non-terraced. Fields with terraces (levels of approximately zero percent slope) were classified as terraced.

2.6.3 Sampling design

To study the effect of SWC on soil properties, soil samples were taken on both of the paired observations in the agricultural fields. Some fields were samples before the start of the raining season and some were sampled during the raining season (short raining season), during a two month of fieldwork. Before the raining season, less effects of nitrogen loss was expected, because less leaching through rainfall has occurred as well as no take-up of available nitrogen by plants. Soil moisture was measured directly in the field, during the raining season. The measurements of the pairs were always taken on the same day in order to avoid influences of temporal fluctuations of the weather on soil properties.

The sampling strategy was different for the (1) intercropping/mono cropping fields and the (2) terraced/non-terraced fields.

(1) Both topsoil (0-20 cm) and subsoil (50-60 cm) were sampled (Edelman auger). For the topsoil, composite samples were taken to reduce the effect of short distance variability. The composite samples consisted out of five samples. The samples were taken in the middle of the field with a distance of approximately five meters, see Figure 7. The sample of the subsoil was taken additionally if there were no limitations to reach this depth, such as presence of rocks or dryness of the soil. There was no composite sample taken for the subsoil, because less variability was expected relatively to the topsoil.

The same sampling design was applied for the soil moisture. However the soil moisture was measured insitu and measurements were only possible during the rainy season.

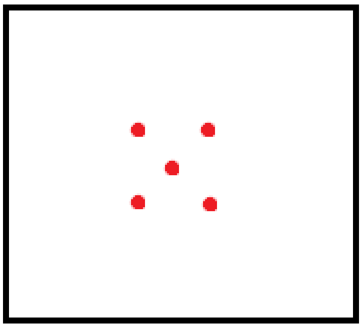

Figure 7. Sampling design for the mono-/intercropping fields. The subsample was taken in the centre. The distance between the samples was approximately five meter. Note that this figure is not the appropriate scale.

(2) For the terraced/non-terraced fields, three composite samples were taken each consisting out of three samples (Figure 8). One composite sample was taken on the top of the terrace/non terraced fields, one in the middle and one on the lower part of the field. This was in order to avoid large deviations from the mean due to the influence of the slope, especially in the non-terraced fields (Herweg and Ludi 1999). One subsample (50-60 cm) was taken additionally if there were no limitations to reach this depth, such as presence of rocks or dryness of the soil. More measurements were taken for the soil moisture because more deviation was expected due to variability in both the terraced and non-terraced fields (due to e.g. effect of runoff and erosion, see 2.3.2). The results can be used to study the within field variability in an additional study. Therefore, approximately 15 samples were taken per field. For the non-terraced fields (Figure 8, left) the additional samples for soil moisture were evenly distributed over the field from top to down. For the terraced fields, more deviation was expected from top to down within one terrace level because the levels might be in development (see 2.3.2). Therefore, the additional soil moisture samples were taken differently (Figure 8, right).

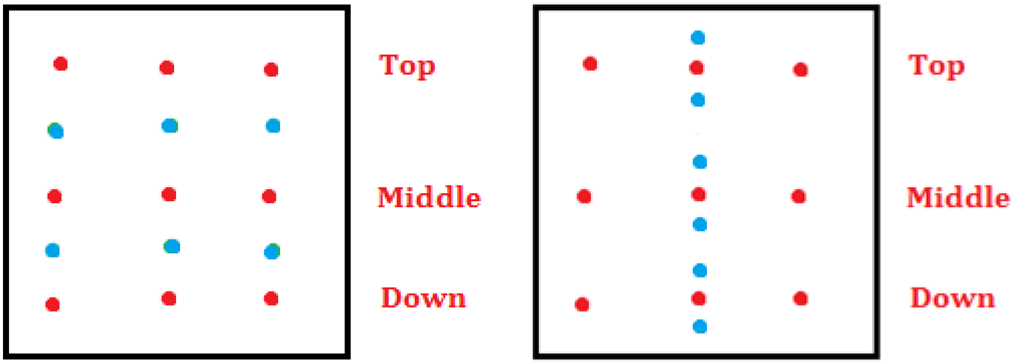

Figure 8. Sampling design for the non-terraced- (left) and terraced fields (right). Three composite samples were taken; (1) top, (2) middle and (3) down (in red). The subsample was taken in the middle. The soil moisture was measured using the same design, but with additionally points (blue).

2.7 Soil analysis

Soil properties

Soil samples were analysed on texture, nitrate content, pH, and the soil moisture was measured directly in the field.

The soil texture is measured to confirm if the pairs were more or less the same. If, for instance, the clay content between the fields are unequal, then also the soil moisture is likely to be different due to differences in water holding capacity. Such influences were prevented by meeting the criteria that soil texture should not differ.

The nitrate content was measured in order to test if the presence of legume (intercropping) significantly increases the nitrate contents in the soil. The nitrate content was also measured in the terraced and non-terraced fields. A higher fertility is assumed in the fields where higher contents of nitrate are measured (see 2.3).

The pH was measured, because lower levels of pH can give an indication of soil degradation (Yan, et al., 1996). The pH significantly influences the availability of plant nutrients, microbial activity and stability of soil aggregates. At lower pH, essential plant macronutrients are less bioavailable than at higher pH (Brady and Weil, 2004).

Soil moisture was measured to test if the presence of terraces leads to a higher content of this property. On the intercropping and mono cropping fields it was measured to test if the presence of legumes could increase the soil moisture. If there is a higher content in nitrate due to the presence of legumes, this could mean creating favourable living conditions for soil organisms. The number of micropores and macropores increases when soil organisms have better living conditions which can lead to a higher water holding capacity. With an increased water holding capacity, a higher content of soil moisture can be expected (Brady and Weil, 2004). An increase in nitrogen can lead to higher crop production, due to a higher supply of nutrients for plants. This results in higher production of organic matter (OM) and therefore SOM. Increased SOM levels, enhances infiltration of rainwater and decreases runoff.

Proximal sensors

Instead of sending samples to the laboratory, proximal sensors were used to analyse the samples. The advantage of using proximal sensors is the relatively quick and easy method and the number of analyses can be large. Additionally, the analyses are relatively cheap compared to laboratory costs.

The samples were analysed within one week after collecting the samples. Before the samples were analysed, the composite samples were mixed intensively and a solution with water was created. Except for the soil texture, the soil-water ratio was 1:1. The solutions were shaken for approximately 30 seconds prior to the measurements. However, the analysis for the soil texture and soil moisture deviates from this procedure. The analysis that is conducted for the soil samples are written below.

Soil texture

Soil texture is measured by a turbiditimeter (AL250T-IR from Aqualitic). This meter is designed to allow fast, precise on-site testing. The unit measures the scattered light at an angle of 90° of liquids in a wide measuring range from 0.01- 1100 NTU, with an accuracy of ± 0.01 NTU (Aqualytic, 2014). The use of this measurement in order to determine the soil texture is described by Stoorvogel et al. (*being edited*). Using the turbidity meter and applying this methodology results in relatively cheap measurements compared to the existing laboratory methodologies.

This procedure uses a similar method as the standard sedimentation methodology applied in laboratories; the sand/silt/clay fractions are measured after 40 sec and 2 hours after the soil has been completely mixed with water. After 40 sec all sand particles are deposited leaving clay and silt particles in the suspension. After 2 hours all sand and silt particles are deposited leaving only the clay particles in the solution. For this research, the NTU measurements are taken after 40 seconds (NTU40) and after 60 minutes (NTU1hr).

Twenty samples are send to the laboratory in duplicate in order to calibrate the NTU measurements on the soil texture. In order to find a relation between these NTU measurements and the texture measurements of the laboratory, the statistical backward procedure is used in SPSS (IBM Statistics 19). No validation is conducted for this study, due to the limited amount of samples analysed in the laboratory.

The proper soil-water solution was defined as 1.23 mL soil: 250 mL water. We used the following equation for the study area:

SAND%=103.285-(1.538*√(NTU40sec)) *(R^2=0.445)*
CLAY%=-0.099+(1.163*√(NTU40sec)) *(R^2=0.523)*

The entire backward procedure can be found in Appendix II.

Nitrate content

Nitrate (NO_3^-) is analysed using the Nitrachek reflectometer (18.4). The Nitrachek offers a simple quick quantitative assessment for the nitrate content of soil/water solutions with a range of 5-500 mg/L, and an accuracy of +/- 1 mg/L. The accuracy of the Nitracheck is verified by (Gulickx et al., 2013) to be accurate (P=0.00, R^2=0.97). A detailed description of how the measurement tool works can be found in (Eijkelkamp, 2004).

pH

The pH of the soil-water solutions is measured by the 18.54 Multimeter (Eijkelkamp, 2014). The meter was daily calibrated (on buffers pH4 and pH7). It has an accuracy of approximately 90-95 percent.

Soil moisture

The soil moisture is measured by the ML3 ThetaProbe Soil Moisture Sensor. The ThetaProbe measures the soil moisture volume percentage by measuring the changes in the dielectric constant. The changes are converted into a millivolt signal proportional to the soil moisture content. The measuring range is of 5 - 55 volumetric moisture content with an accuracy of 5% (Eijkelkamp, 2013).

2.8 Data analysis

2.8.1 SWC

To get insight in the number of farms applying SWC and which one(s), basic statistics is applied for the results of the field observations and household surveys (Microsoft Excel 2010).

2.8.2 Effect of SWC on soil properties

The effect of SWC is tested by using the paired sampled T-Test; paired two sample for means, using the data analysis tool in Excel (Microsoft Excel 2010). The one-tailed results of the test will be used for analysis with a significance level of $\alpha=0.1$. Prior to this analysis, the assumption of normal distribution is tested, using Q-Q plots in SPSS (IBM Statistics SPSS 19).This statistical test is used to compare the means of the paired fields.

2.8.3 Effect of SWC on simulated water-limited yields

To test whether SWC has an effect on the simulation of water-limited yields, the WOFOST model was used. The WOFOST model does a quantitative analysis of the production and growth of annual field crops (see 2.3.2).

The inputs for the WOFOST crop-growth model are: field capacity, crop phenology and weather conditions. Before the soil properties could be used as input for the model some calculations were needed. First, the nitrate contents needed to be converted to organic matter content (OM). Soil texture and OM were then used to calculate field capacities through pedotransfer (PTF) functions.
For the simulations of the current yields for SWC and no SWC, the inputs of weather conditions and the soil properties varied. The weather condition were different for the simulations per year, but equal between the paired fields. The soil properties were different between the paired fields. This also accounts for the simulations of future yields. Only the soil properties of the topsoil are used for the simulations, because of the limited amount of subsoil that could have been analysed. For the weather conditions however, the climate scenarios for 2050 were used. For all simulations, the crop phenology remained equal.

In Figure 9, a schematic overview is given of the steps which are taken for the simulation of current and future water-limited yields. These steps are described in detail below.

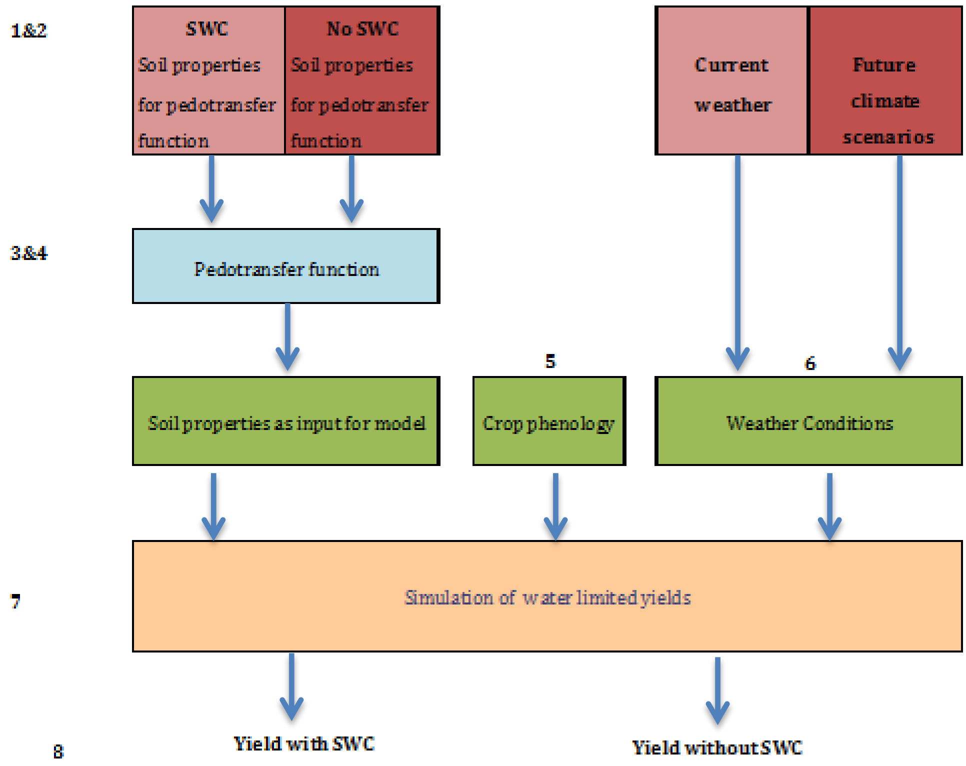

Figure 9. Schematic overview of steps (1-8) taken towards the simulations of water-limited yields

1. Nitrate, which is measured in the field, is converted to OM. To obtain the measurements for OM, a C:N ratio calculated from the measured C and N of the laboratory is used to obtain the total C content. The C:N ratio is assumed to remain constant in the study area, because the C:N ratio of the organic material added to the fields were not extremely different; management practises of farmers are relatively equal of the fields as well as the grown crops. Although relatively higher nitrate levels may be expected in the intercropping fields, also higher amounts of carbon is expected. Higher contents of nitrate in the soil likely increases fertility and therefore production of organic matter, and therefore carbon.

   First, the nitrate (NO_3^-) is converted to total N, using the atomic mass; NO_3^- multiplying by 0.226. After this conversion, the N levels are multiplied by +/- 11, to obtain the C levels. Converting C to OM is done by multiplying C with 1.72, because OM contains approximately 58% C (Hoffland, 2013).

2. The slopes are used to estimate the runoff fractions of the terraced and non-terraced fields. The runoff is calculated as a fraction of rainfall that does not infiltrate into the soil. In Table 3, the estimated runoff fractions are shown, based on the drainage class and slope. A literature search on the fraction of total seasonal rainfall lost by surface runoff in Sub-Saharan Africa was performed to come up with these fractions. The drainage class is determined by existing data for soil profiles in this study. The exciting data is derived from the Kensoter database. The Kensoter database contains soil profile data for Kenya on a scale of 1:250,000 (Hudson, 1988; ISRIC, 2014). Different soil properties, such as soil depth, horizons, texture etc. can be found in this database.
   The soils in our study area are classified as well drained, therefore, only these classes will be used. Soil depth is also derived from the Kensoter database. The soil depth always remained 1m.

Table 3.Surface runoff fraction of total rainfall (in %) for soil cultivated with cereals (GYGA,2014)

Drainage class, Slope angle, in %	Very poor	Insufficient	Moderate	Well drained	Extremely well drained
0-2	20	13.3	6.7	0	0
2-6	26.7	20	13.3	6.7	0
6-10	33.3	26.7	20	13.3	6.7
>10	40	33.3	26.7	20	13.3

3. In order to determine the impact of OM (%), clay- and sand fractions on the model for PTF functions (see below) individually, a sensitivity analysis is carried out by systematically increasing one of the inputs by 10% while keeping other inputs constant. The starting values for the inputs were based on the proportion of the different soil properties. For instance, if the most of the clay fractions were found between 0.5 and 0.7, then the sensitivity analysis started at 0.5.

4. PTF functions were needed in order to obtain the required data for the field capacities of the soil. Field capacity is the amount of water held in the soil after excess water has drained away and the rate of downward water has decreased (Klute, 2003). The field capacity is determined by the upper and lower soil limits for water retention such as field capacity, based on soil texture and organic matter. These PTF functions are developed by Saxton and Rawls (Saxton and Rawls, 2006). The authors developed new soil water characteristic equations based on the current available USDA soil database using soil texture and OM. This function was satisfactorily calibrated and evaluated based on USDA soil profiles data (GYGA, 2014). The physical definition of field capacity (expressed symbolically as θ_{33}) is the bulk water content retained in soil at −33 J/kg (or −0.33 bar). In this study, these equations are used to determine the field capacity. The equations are summarized as followed:

$$\theta_{33t} = \mathbf{-0.251}S + \mathbf{0.195}C + \mathbf{0.011}OM + OM + \mathbf{0.006}\,(S \times OM)\ \mathbf{-0.027}\,(C \times OM) + \mathbf{0.452}\,(S \times C) + \mathbf{0.299}$$

θ_{33t}	Soil moisture at field capacity (% volume percentage)
S	Sand fraction
C	Clay fraction
OM	Organic matter (%)

The field capacities are calculated for all measurements in the field. Different field capacities were used for all simulations of water-limited crop yield.

5. The crop phenology are derived from experts working in the GYGA program. The crop phenology contains information such as length of growing cycle and photosynthetic characteristics. For this research, maize is used as crop. This input will remain constant during the study.

6. The required weather data to simulate the data for the water-limited yields is daily information about: maximum temperature, minimum temperature, rainfall, wind speed,

irradiation and early morning vapour pressure. This information is derived from the weather station (Kambi Ya Mawe) located in the middle of the study area. There was information available for the years 2004 until 2012. For the simulations, three years were simulated; the driest-, wettest- and an average year for the available years. The driest- wettest -and average years were estimated by the amount of precipitation for the short raining season. This season is chosen because the soil samples were taken and analysed during this period. The simulations of those three years are conducted in order to study if the presence of SWC have different effects in more extreme years.
Sowing dates and start of the water balance are needed to run the model and is depended on the climate conditions; sowing is often done just before the start of the raining season. Sowing dates are established on the days where 10 mm rainfall event occurred, followed by at least five days of rain. The start of the water balance is derived by the sowing date minus 30 (GYGA, 2014).

For the simulation of the yields for the different climate scenarios in a later stage, data is derived from Worldclim (Version 1.4). WorldClim (Worldclim, 2014) contains sets of global climate layers with different spatial resolutions (Hijmans et al., 2005). The data contained in these layers are monthly precipitation and the mean minimum, and maximum temperature estimated for each climate scenario for 2050. Worldclim also contains layers of the current weather conditions (averaged over 1950-2000). Relative differences between the current weather conditions and the four different climate scenarios were calculated and expressed in percentages. These percentages were multiplied by the current weather derived from the Kambi Ya Mawe station. This opened opportunities to create daily weather conditions for the four climate scenarios in 2050. Also here, simulations are conducted for the driest- wettest -and average years of the short raining season. This means that in total 12 climate scenarios are created for 2050.
The sowing dates and start of the water balance were established on the same manner mentioned in step 6.

7. Prior to the simulations of water-limited yields, a sensitivity analysis is conducted in order to estimate the impact of the soil properties and runoff fractions of the outputs. The sensitivity analysis for the model is carried out for the runoff, clay- and sand fractions and OM percentages. To analyse the clay- and sand fractions as well as OM content for the sensitivity analysis, the field capacities for each property from the sensitivity analysis of the SPAW model are used as input for the WOFOST crop-growth model. The driest, wettest years and an average year was chosen as weather conditions because these are expected to have a large impact for the simulations of yield.

8. To compare the yields between the presence of SWC and no SWC, T-tests are conducted in order to compare means. The one-tailed results of the test will be used for analysis with a significance level of $\alpha=0.1$.

3 Results and discussion

3.1 Soil water conservation in the study area

This paragraph shows the results of the surveys of the visited agricultural fields.

In Table 4, the proportion of the current SWC that were found in the study area are shown. In total, 88 agricultural fields were visited and almost 90% applied a SWC strategy. The type of applied strategies were often depended on the traditional backgrounds of previous generations. In Figure 10 and Figure 11 an example of a terraced field and an intercropped field is shown.

The agricultural fields were often not found randomly where it was necessary to create pairs for the paired-sampled T-test. Therefore the percentage of the no SWC strategy applied is likely overestimated in the study area. Intercropping forms the largest group; more than half of the agricultural fields applied intercropping. In Figure 12 an overview is given of the crops that were being intercropped with maize. The numbers are more or less evenly distributed; farmers often intercropped all these crops with maize rather than one specific crop. The main reason for this was to reduce the risk of total crop failure.

Table 4. The SWC practises found in the study area of Makueni

SWC practises found in Makueni	Number of fields	Proportion
Intercropping and terracing	21	23.9%
Only intercropping	54	61.4%
Only terracing	3	3.4%
None	10	11.4%
Total visited fields	88	

Figure 10. A terraced field in Makueni

The large percentage of 'only intercropping' (Table 4) implies that a large amount of farmers did not apply terraces. However, not all agricultural fields have to be terraced; according to Herweg (Herweg, 1999) the need of placing terraces in order to benefit starts with a slope of five percent. Where the slopes were bigger than five percent, 72% of the farmers applied terraces.

Reasons not to apply terraces were often lack of labour/money, but farmers often aimed to place terraces in the near future. However, also here is important to mention that those fields were not visited randomly. Therefore, the total amount of farmers that applies terraces is likely higher in our study area.

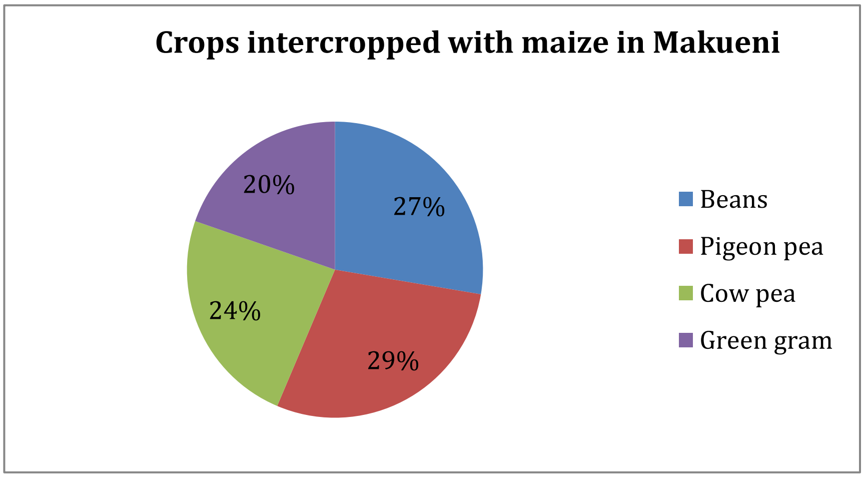

Figure 12. The proportion of crops being intercropped.

Figure 11. An example of intercropping. Here the maize is intercropped with beans

3.2 Effect of soil water conservations on soil properties

In total 11 couples could be studied for both pairs. It was found that the Q-Q plots were normally distributed for all soil measurements. There was tried to minimize side effects such as management and slope. This was not always possible. An overview can be found in Appendix III.

3.2.1 Intercropping and mono cropping

Intercropping did not have a large effect on the soil properties. In Table 5, a summary of the results of the measurements are shown for the different soil properties, for both top- and subsoil. In general, no large differences are found between intercropping and mono cropping. For a complete overview of all measurements of the pairs, see Appendix IV.

Applying intercropping or mono cropping had no significant effect on soil moisture (Sig.= 0.18). The expectation was that there could be a difference due to increased production of organic matter on intercropping fields, due to the higher amount of available nitrate. Organic matter increases the water holding capacity of soils (Hoffland et al., 2013). However, most of the built up organic matter is removed from the soils after the growing season to feed the cattle. For the subsoil, the differences are a little bit larger, however, yet not significant. The numbers are based on one measurement per field and possibly do not give an accurate indication of the current soil moisture percentage of the entire field. Additionally, sometimes the samples were taken on a different depth, or even not taken at all. This was because it was not always possible to go deeper due to stones in the profile or the dry parts in the soil. More accurate results of the subsoil are expected more during the raining season when more infiltration has taken place.

The pH of the mono cropping and intercropping fields were very similar within the margin of the method. This implies that applying either mono cropping or intercropping does not have an effect on the soil pH, for both the top- and subsoil (Sig.= 0.31). This is in agreement with literature, because there is often a balance in pH and legumes (Yan et al., 1996). During the growth of legumes, soil is acidified due to proton release from roots. As a consequence, plants accumulate organic anions which neutralize the soil acid when roots are decomposed in the soil. There is also often a balance between pH and non-legumes. These results are therefore not surprising. In one of the couples however, small difference were found, likely due to the application of fertilizer a few weeks before. Applying fertilizer can lead to a decrease of pH due to effects of ammonium that undergoes nitrification to nitrates (Brady and Weil, 2004).

Applying intercropping or mono cropping had a significant effect on the nitrate content of the topsoil (Sig.= 0.07). This confirms that intercropping legumes indeed increases the nitrogen content of the soil (Brady and Weil, 2004). However, the effect of inter/mono cropping does not have an extreme effect when analysing Figure 13. Due to the big difference in couple five, a significant effect can be shown. There is no clear explanation why the NO3- content in this couple is very different, although a random error might be the case. No significant difference is found between the mono- intercropping fields of the subsoil. However, relatively few samples are analysed compared to the topsoil. Additional measurements will increase the accuracy of the results for the subsoil.

By applying intercropping as SWC strategy, it improves soil conditions by increasing the nitrate levels of the topsoil. The addition of N in the soil, likely leads to higher fertility and therefore an increase of crop-production is expected. If these increased levels have an effect on the current water-limited yields, is tested later in this study.

Table 5. T-test of paired observations for mono cropping and intercropping fields

			Paired observations			
Depth (cm)	*Soil property*		*Mono cropping*	*Intercropping*	*df*	*Sig*
0-20	Soil moisture (%)	Mean	22.5	23.8	10	0.18
		SD	7.3	5.8	10	0.17
50-60		Mean	19.7	18.1	9	0.15
		SD	5.9	8.6		
0-20	pH	Mean	6.2	6.2	10	0.31
		SD	0.3	0.4		
50-60		Mean	6.4	6.1	6	0.13
		SD	0.4	0.6		
0-20	Nitrate (mg/L)	Mean	38.0	45.4	10	**0.07**
		SD	16.6	22.3		
50-60		Mean	23.4	20.4	6	0.26
		SD	6.6	10.2		

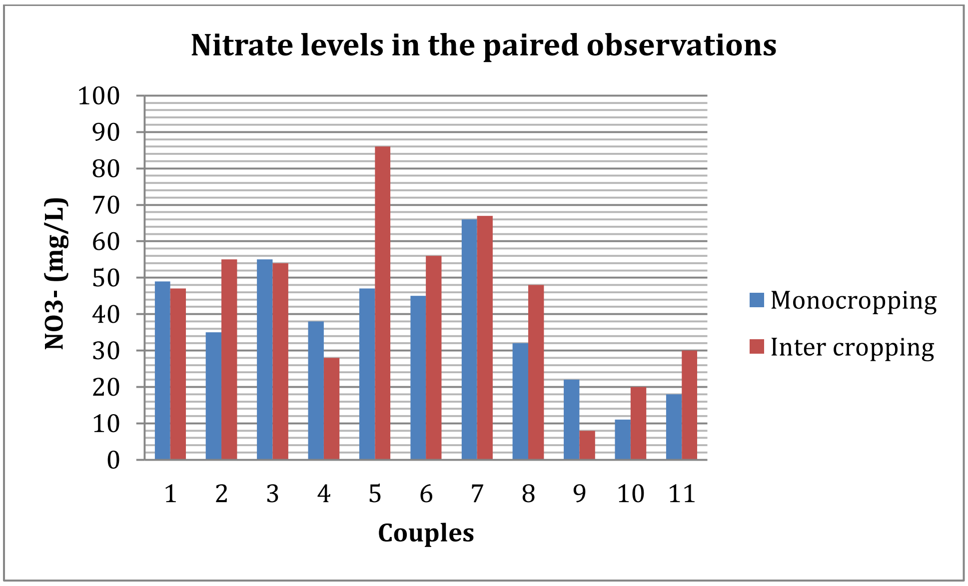

Figure 13. Nitrate levels in the paired observations for intercropping and mono cropping

3.2.2 Terraced and non-terraced fields

By applying terraces, no large effects on soil properties were observed. In Table 6, a summary of the results of the measurements are shown for the different soil properties, for both top- and subsoil. Except for the soil moisture, no large differences are found between the terraced and non-terraced fields. For a complete overview of all measurements of the pairs, see Appendix IV.

Soil moisture of the non-terraced fields is significantly lower in the terraced fields (Sig.=0.03). There was also a significant difference in the standard error of soil moisture between the fields (Sig.=0.02). On average, the soil moisture seems to be less variable in terraced fields than in non-terraced fields. This confirms the theory that by applying terraces soil water remains more stable (Herweg et al.,1999). In Figure 14, the soil moisture of the terraced and non-terraced fields are shown. In general, the terraced fields show a higher- or an equal percentage of soil moisture. In couple number two, seven and nine, the average moisture content of the non-terraced fields are based on less observations than the terraced fields. Sometimes it was not possible to get a sample in the non-terraced fields on both 0-20 cm depth and 50-60cm depth. These observations are left out during the calculations, assuming that these observations would have the same average as the other observations. However, this assumption is possibly unrealistic. Including these observations with a soil moisture of zero percent might be more realistic because often the soils were too dry to measure. The significant difference is higher in this case (Sig.= 0.01). However, in some cases the amount of gravel was too high to be able to measure. It is unknown if these observations can be treated as zero percent.

Table 6. T-test of paired observations for terraced and non-terraced fields

			SWC strategy pairs			
Depth (cm)			*Terraced*	*Non-terraced*	*df*	*Sig*
0-20	Soil moisture (%)	Average	22.6	19.1	10	**0.03**
		SD	5.5	6.3	10	**0.02**
50-60		Average	18.3	15.6	8	0.17
		SD	10.6	18.2		
0-20	pH	Average	6.0	6.0	10	0.50
		SD	0.1	0.3		
50-60		Average	6.1	6.1	5	0.48
		SD	0.4	0.2		
0-20	Nitrate (mg/L)	Average	50.9	45.1	10	0.23
		SD	28.0	31.7		
50-60		Average	19.3	20.1	5	0.46
		SD	14.0	7.8		

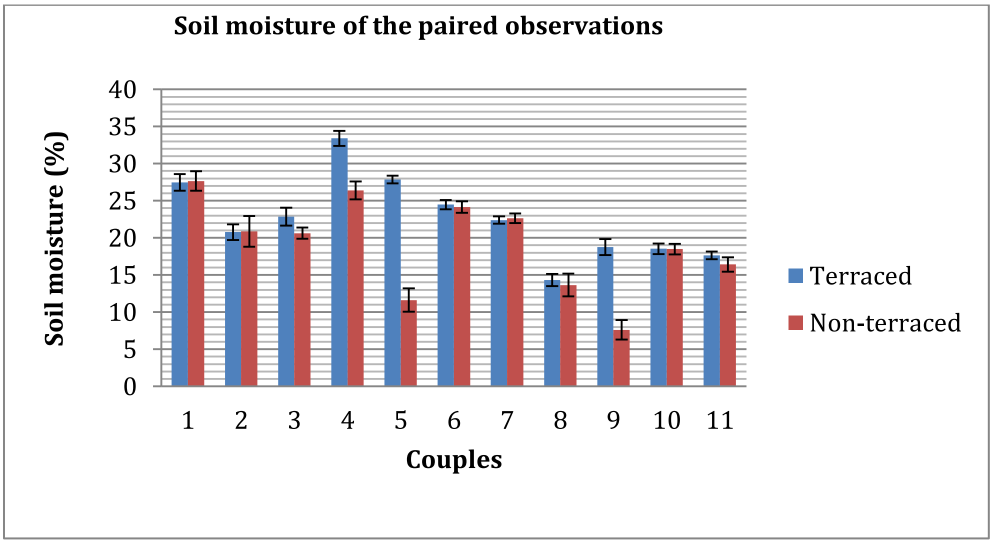

Figure 14. Soil moisture of the paired observations for the terraced and non-terraced fields

The soil moisture of the subsoil did not show a significant difference between the terraced and non-terraced fields. The average of the subsoil in the terraced fields is higher than the non-terraced fields. The amount of subsamples taken per field are limited in the non-terraced fields due to impossibilities reaching the subsoil. The amount impossibilities of reaching the subsoil in the non-terraced fields can also give an indication of the dryness of the soils. Obtaining more samples of the subsoil would give more accurate results of the differences between the field.

No significant difference of the pH on the terraced and non-terraced fields is found (Sig.=0.5). On average, the pH of both fields are more or less the same so no clear sign of soil degradation is found. This also accounts for the subsoil (Sig.=0.48). However, terracing is often stimulated to avoid soil degradation (Tiffen et al., 1995). This raises the question whether soil degradation is indeed higher in non-terraced fields or if this is over estimated.

For the nitrate levels of terraced and non-terraced fields also no difference were found (Sig.=0.23). Surprisingly, the nitrate levels are on average higher in the non-terraced fields. This is surprising because often the non-terraced fields were never manured where this was more often the case for the terraced fields. Reasons that the non-terraced fields are often higher in nitrate content could be that the terraced fields are often more intensively used than the non-terraced fields. Therefore, the take-up of nutrients would be higher and the resulting nitrate levels in the soil lower. The variation of the nitrate levels in the terraced fields are relatively high compared to the non-terraced fields. This is can be due to the recent application of manure at one of the terrace levels which results in higher contents of nitrate than the other terraces.

By applying terracing as SWC strategy, it improves soil conditions by increasing the soil moisture of the topsoil. Soil moisture conservation is crucial for crop production in many semi-arid areas such as in Makueni. If terracing increases the current water-limited yields is tested later in this study.

3.3 Sensitivity analysis

3.3.1 Pedotransfer function

Prior to the simulations of the water-limited yields a sensitivity analysis is conducted to estimate the impact of the soil properties on the outputs of the PTF (SPAW model) as well as for the crop-growth simulation model (WOFOST). This is done by systemically increasing one of the inputs (OM, clay and sand) by 10%.

The starting values are based on the distribution of the results for OM, clay and sand; the values with the highest frequencies/range are used as starting values. The histograms of these values are shown in Appendix V.

The results of the sensitivity analysis are summarized in Table 7. The clay fraction had the biggest impact on the outputs (Slope= 0.573) while the OM percentages had little impact (Slope= 0.011). This means that the OM content have very few impact on the field capacities compared to the presence of clay and sand.

The SPAW model is not very sensitive to organic matter (Figure 15). Increasing the OM content from 1 to 2.4(%) results in an increase of 0.015 volume% for the field capacity (slope: 0.0107).

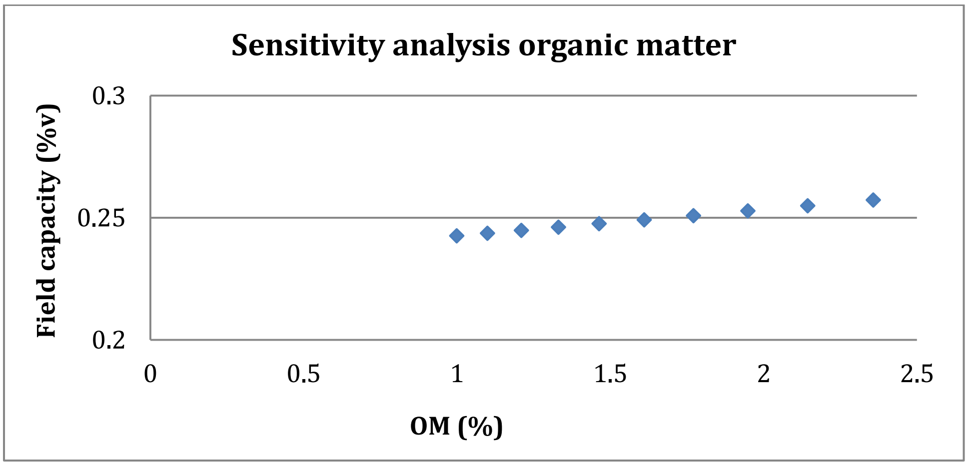

Figure 15 Sensitivity analysis for organic matter of the SPAW model.

Sand is more sensitive than OM (Figure 16). Increasing the sand fraction from 0.4 to 0.71 leads to a decrease in field capacity (%v) from -0.055 (slope: -0.178).

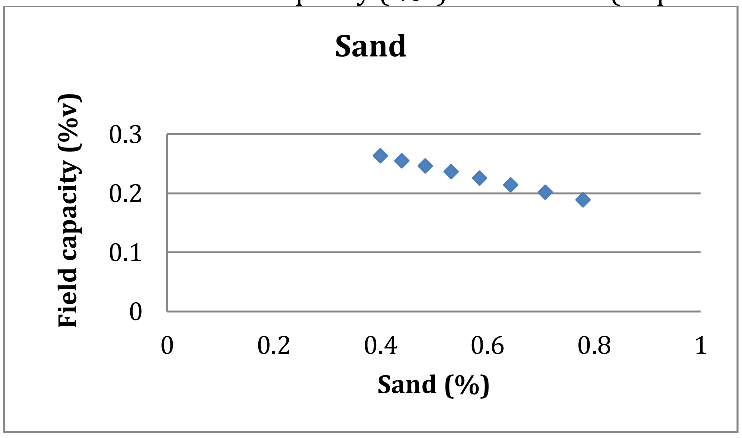

Figure 16. Sensitivity analyses for sand of the SPAW model.

The most sensible input parameter for the SPAW model is clay (Figure 17). Increasing the clay fraction from 0.2 to approximately 0.5 leads to a change of 0.155 in field capacity (v%) (slope: 0.570).

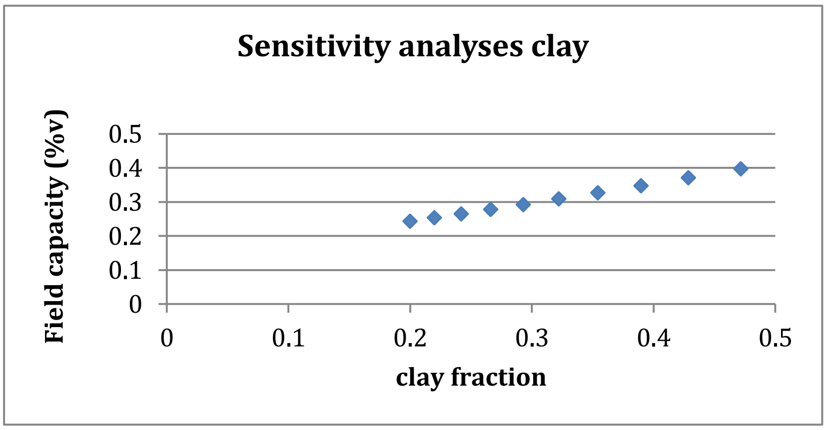

Figure 17. sensitivity analyses for clay of the SPAW model

For estimating soil hydraulic properties by soil texture and OM using statistical analysis, extreme values were left out by the authors. Samples with an OM >8% and clay > 60% were omitted (Saxton, 2006). No samples showed OM contents higher than 8% in our study. Although very few, some soil samples taken in the study area did have a clay content higher than 60%. According to Balland et al., (2008), the PTF projections might become inaccurate outside these constraints. Additionally, the PTF functions are resulting from a wide range of data from the USDA soils. These soils generally have higher contents in OM than the soils found in Kenya. The PTF function might therefore be less accurate in estimating field capacities with low amounts of OM.

Table 7. The result of the sensitivity analysis of the SPAW model for the different soil properties

Soil property	Range	**Difference in moisture content at field capacity (v%)**	**Slope**
OM	1-4.5%	+ 0.026	0.011
Clay fraction	0.2-0.47	+ 0.155	0.573
Sand fraction	0.4-0.78	-0.075	- 0.197

3.3.2 Crop-growth simulation model

For the sensitivity analysis of the crop-growth simulation model WOFOST, three years are simulated. The driest-, wettest- and an average year are used for the simulations (Table 8). These years are chosen to observe the importance of different soil properties and slope in more extreme years compared to an average year. In Figure 18, the distribution of precipitation is shown. The wet year shows significantly more peaks above the 10 mm line compared to the average year, whereas the dry year shows significantly lower peaks.

Table 8. Amount of rainfall in short raining season in Makueni

Short raining season	Precipitation (mm)
Dry year (2007)	131.2
Average year (2011)	205.4
Wet year (2012)	407.4

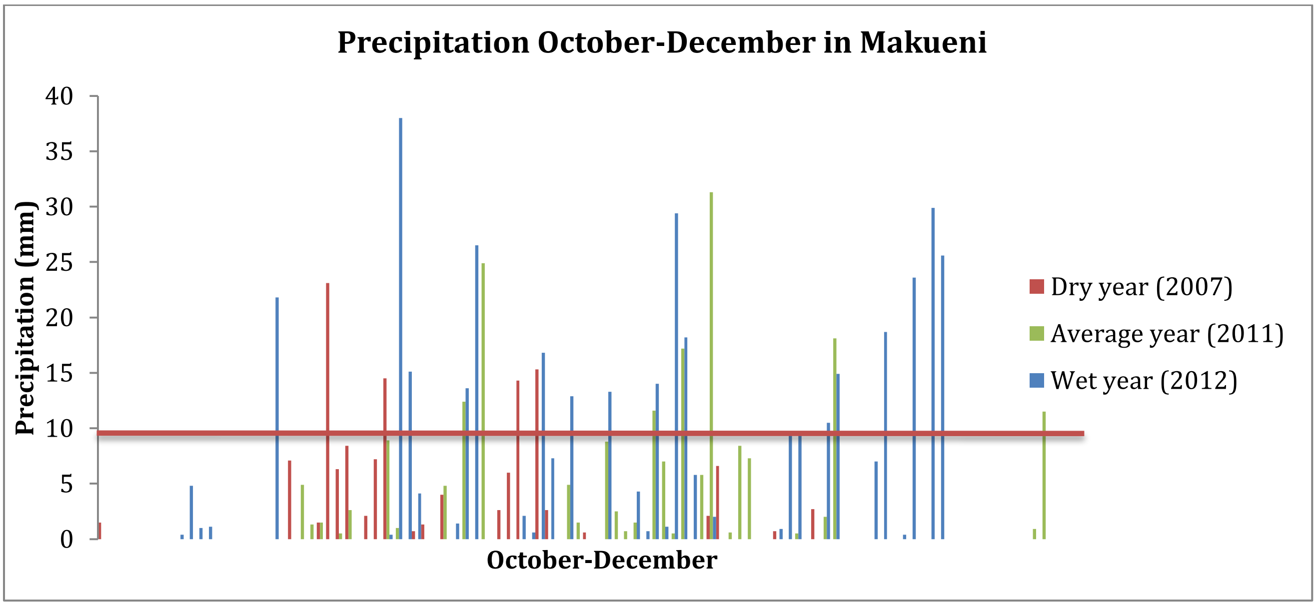

Figure 18. Precipitation in the short raining season

A summary of the results of the sensitivity analysis can be found in Table 9. The OM and runoff fractions had the lowest impact on the simulations of yields for all years, while sand and clay fractions had relatively large impacts.

For all the properties, the model was most sensitive for the simulation of water-limited yield of the dry year. Especially the runoff has a big effect on the simulation of yields in a dry year (Figure 19). This can be explained by that the water supply to plants is already lower and if additionally water runs off this will lead to water stress for plants. This effect is lower in the average and wet year.

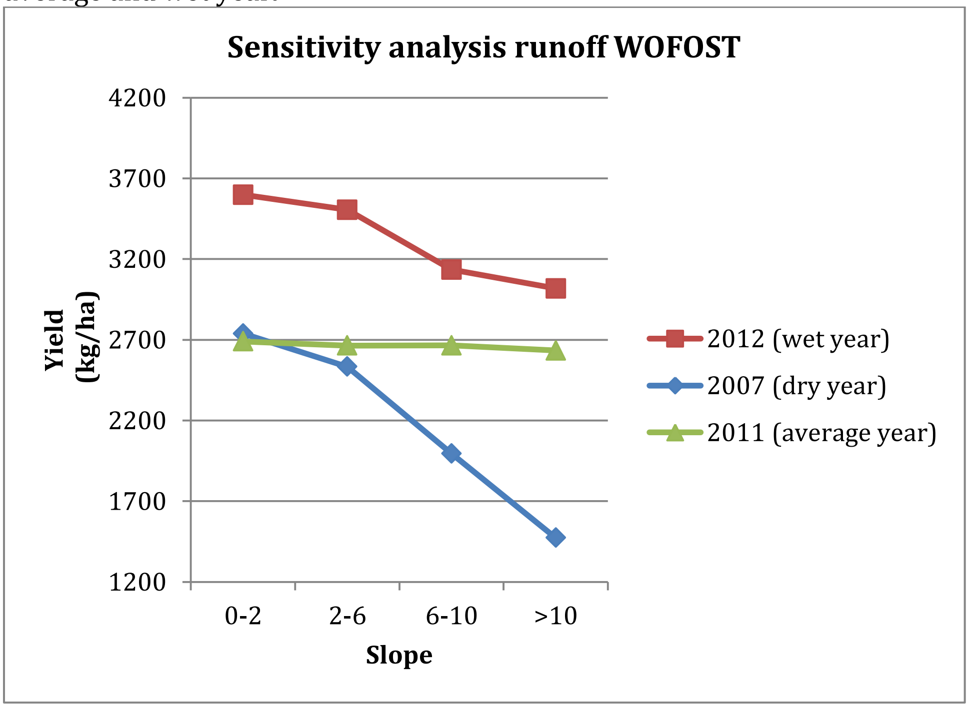

Figure 19.sensitivity of the slope on WOFOST

For OM the model was three times more sensitive in a dry year, compared to an average year (Figure 20). OM leads to higher field capacities, as observed in the previous chapter. Especially in dry years the capacity of the soil to hold water is essential for water supply to plants. By increasing the OM and therefore the field capacity, the water supply to plants is possibly more stable and prone to droughts. This could explain the importance of field capacities for the determination of yields in a dry year.

Table 9.Summary of the sensitivity analysis on WOFOST

		2007 (dry year)		2011 (average year)		2012 (wet year)		
		Yield difference	Slope	Yield difference	Slope	Yield difference	Slope	*Slope*
Soil property	Range	(kg/ha)	Graph	(kg/ha)	Graph	(kg/ha)	Graph	*average*
OM	1-4.5%	+853.0	347.8	+273.0	111.3	+533.0	217.3	225.5
Clay fraction	0.2-0.43	+2101.0	9186.0	+945.0	4131.7	+1144.0	5001.8	6106.5
Sand fraction	0.4-0.78	-2088.0	-7375.0	-889.0	-2342.6	-1399.0	-3686.6	-4468.1
Slope for runoff	0-10 %	+1266.0	-126.6	+56.0	-5.6	+581.0	58.1	-24.7

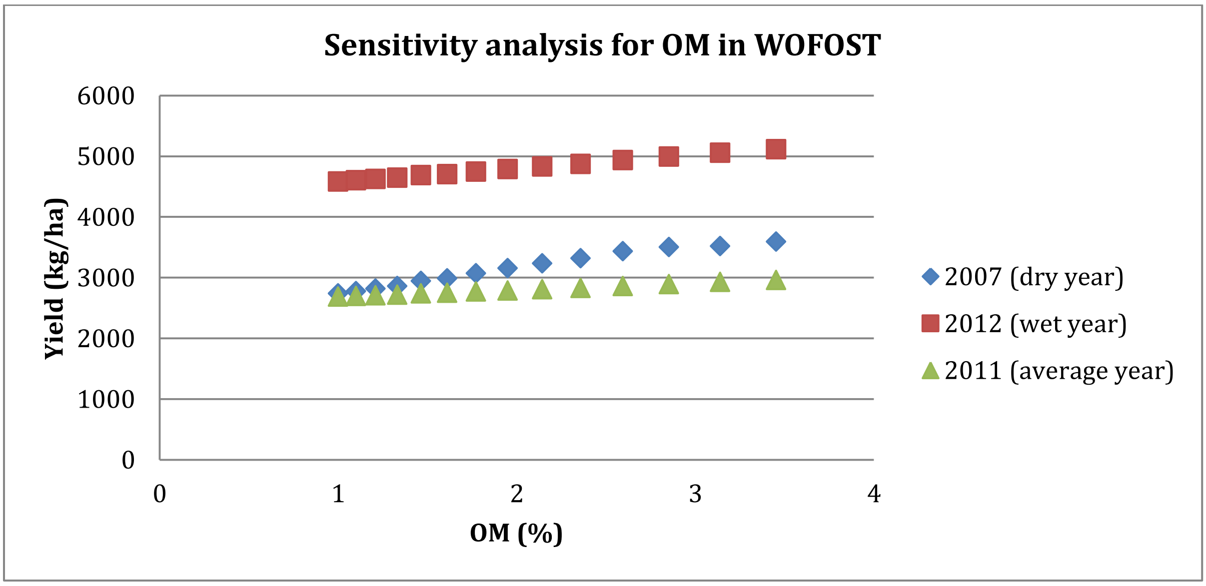

Figure 20.Sensitivity analysis of OM on WOFOST.

For sand, the higher yields are simulated for a dry year compared to an average year, when the sand fraction is 0.4 (Figure 21). However, the opposite is observed when sand fractions are >0.5. Higher sand fractions result in lower field capacities. As mentioned before, field capacities are important for the determination of yields in a dry year. Therefore, the yields seem to be more stable in an average year with increased sand fractions, compared to dry years; the supply of water to plants is less evenly distributed which results in lower yields.

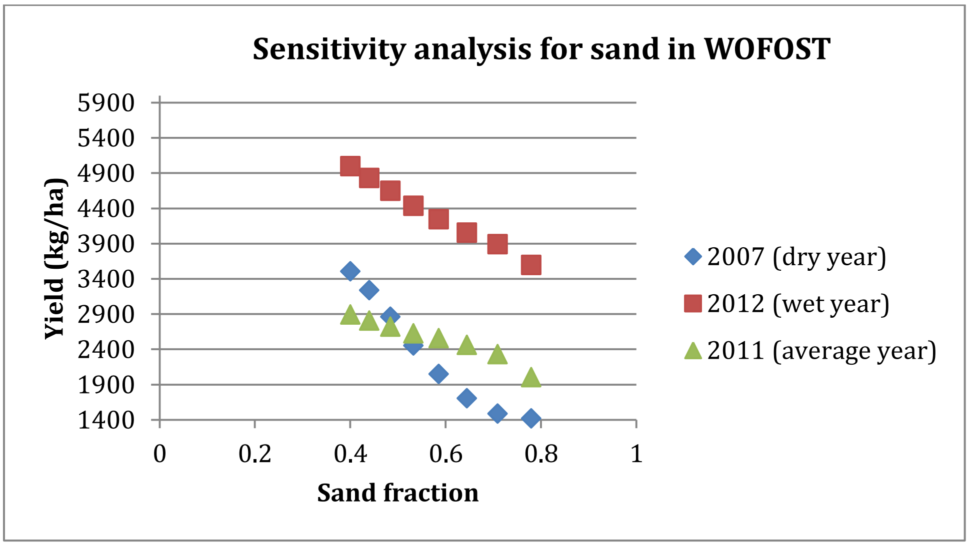

Figure 21. Sensitivity analysis for sand fractions.

The model was most sensitive to clay fractions on average. Higher contents of clay leads to increaded field capacities. Also here, the model is most sensitive with the simulation of dry years. In a wet- and average year the model becomes less sensitive when clay fractions are higher than 0.3 and 0.35 respectively. This implies that the yields do not increase anymore with higher field capacities. This implies that for these years, the yields are possibly on its potential production; water supply is not a limiting factor for the determination of yields.

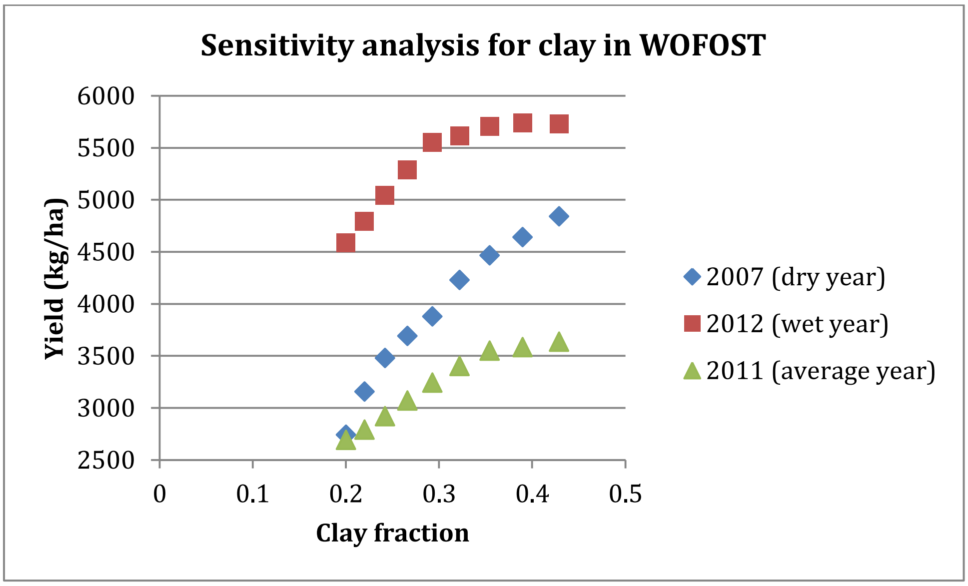

Figure 22. Sensitivity WOFOST for clay fractions.

3.4 Effect of soil water conservation on current climate scenarios

Water content at field capacity, runoff and water-limited yields

In this chapter we observed if the measured differences in soil properties also result in increased crop yields.

The effect of nitrate content between the paired fields was incorporated by converting nitrate to OM, followed by the calculations to the field capacities based on OM, clay- and sand content. The sensitivity analysis of the SPAW model seemed to be relatively sensitive to clay and sand contents compared to the OM content. To analyse the effect of OM contents of the paired fields of intercropping and mono cropping on the outcomes of the simulation of water-limited yields, the clay and sand fractions were therefore kept equal between the fields by taking an average between the pairs. This is done in order to avoid differences in field capacities due to clay or sand fractions rather than the OM contents. In Appendix VI, the results of the calculations for OM contents and field capacities are shown. This was not done for the analysis of the terraced and non-terraced fields, because the focus for the simulation of water-limited yields was lain on the effects of runoff rather than OM content. Therefore, the direct inputs of the field capacities were taken rather than an average between the fields. An overview of the runoff and field capacities are given in Appendix VI.

As mentioned before, the field capacities might be less accurate because the clay fractions are sometimes outside the PTF projection range and the low contents of OM in Kenyan soils compared to the USDA soils might give deviations as well. However, it is not known how this would affect the field capacities.

The maize yields simulated by the model are expected to be different compared to the actual yields (1597 kg/ha per growing season (Claessens et al., 2008)) due do several reasons. First of all, the WOFOST model does not incorporate influences such as pest and diseases and presence of weeds, which causes decreases in crop yields. Additionally, the nutrient-limited yields were not simulated. However, the lack of soil nutrient supply are often –next to- water supply, the main constraining factor for crop production in Kenya (Barron 2004). At last, only information of the topsoil is used for the simulations. Because the topsoil is often higher in OM content (Brady and Weil, 2004), this results in higher field capacities than if the subsoil would also be taken into account.
Nevertheless, the effect of water-limited yields for the SWC and no SWC can still be observed relatively. However, one should be careful with comparing the model outputs with the actual yield data.

3.4.1 Intercropping and mono cropping fields

For the simulations of the current water-limited maize yields three years are chosen, determined by the amount of precipitation; a wet year, a dry year, and an average year (Table 8).

There are no big differences in water-limited yields between the intercropped- and mono cropped fields (Table 10). The biggest percentage of yield increase by applying intercropping is found in a dry year, although not significant (Sig.=0.16). The increase in yields are explained by an increase in the field capacities. The field capacities were different between the paired fields for the simulations, due to higher contents of OM. When the field capacities are higher, it means an increase of the water holding capacity of the soil, assuming an equal rooting depth and wilting point (Hedley et al. 2009). The water holding capacity determines the available water that can be stored in the soil and is available for growing crops. If the water holding capacity is higher, the soil can store more water and more resilience exists towards long time droughts. Because droughts are problematic in Kenya for crop production, it forms an important factor for the production of crops, and can therefore leads to higher simulations of yields.

Although the differences are not significant for water-limited yields, an increase in yield can be expected if the nutrient-limited yields would be simulated. The nutrient-limited yields are determined by the amount of plant nutrients needed to attain potential and water-limited production levels. One of these nutrients is nitrogen. Because the effect of intercropping was significant (Sig.=0.07, Table 5) on the nitrate levels of the topsoil, it would likely lead to a significant increase of yield. However, due to current limitations of the model, these simulations are not taken into account.

Table 10. Results of water-limited yields for the intercropping and mono cropping fields

Years	**Precipitation (mm)**	**Min. Temp**	**Max. Temp**	**Average yield (kg/ha)**			
	October-December	˚C	˚C	*Mono cropping*	*Intercropping*	Yield difference	*Sig.*
'Dry year' 2007	131.2	20.5	28	2434.0	2481.9	+2.0%	*0.16*
'Average year' 2011	205.4	18.2	27.9	2424.7	2464.9	+1.7%	*0.14*
'Wet year' 2012	407.4	18.5	28.2	6130.0	6184.4	+0.9%	*0.13*

3.4.2 Terraced and non-terraced fields

The simulation of water-limited yields resulted in significant higher yields for the terraced fields in the dry year (Table 11). The difference in yields between the pairs is mainly due to the effect of runoff in the non-terraced fields. The runoff is established by assuming that a fixed fraction of rainfall is lost and does not infiltrate to end up as soil moisture. Because the terraced fields have a slope of zero within one terrace level, there is no or a negligible amount of runoff of rainwater. As a result, more rainwater infiltrates into the soil and relatively more water is available to plants, which enhances the total crop production. The advantage of terracing is the biggest in the dry year. For the dry year, an increase of 50% is found (Sig.=0.02). In a dry year, the demand for water by plants is relatively big compared to an average- and wet year where there is more supply of water due to precipitation. Low amounts of runoff due to terracing results in an increased and better distribution of water supply, and therefore in higher water-limited yields.

The runoff fractions are resulting from literature search on the fractions of total seasonal rainfall lost by runoff in Sub-Saharan Africa depending on soil drainage class and slopes (GYGA 2014). Although slope and soil drainage class are probably the most important factors to estimate the runoff fractions, the runoff is also depended on other factors such as the rate and intensity of rainfall and length of slope (Chaplot et.al., 2003; Brady and Weil, 2004). Therefore the runoff values possibly deviate from 'true' runoff values. Additionally, the runoff classifications are quite large and implies that a slope of 10% or a slope of 30% results in the same runoff, which is highly unlikely. Site specific runoff values by e.g. field experiments would give a higher accuracy of runoff, but is outside the goal of this research. Nevertheless, these numbers can still give an indication of the effect on terracing and non-terracing on the simulations of yield because slope gradient is often seen as the most defining factor for determining run-off (Chaplot et.al., 2003).

Additionally to loss of water, there might also be loss of soil and therefore nutrients. This was often observed during the fieldwork when the non-terraced fields were visited. The presence of gullies within the field, gave an indication of this process. A loss of nutrients could result in a decrease of crop yields.

CCAFS promotes these strategies as climate adaptation strategy. The results of the simulations for water-limited yields for terraces however, imply that these strategies are very effective under the current climate conditions as well, especially under more extreme weather conditions.

Table 11. Results of water-limited yields for the terraced and non-terraced fields

Years	**Precipitation (mm)**	**Min. Temp**	**Max. Temp**	**Average yield (kg/ha)**			
	October-December	**˚C**	**˚C**	*Non-terraced*	*Terraced*	Yield diff	*Sig.*
'Dry year' 2007	131.2	20.5	28	1970.8	2964.6	+50.4%	***0.02***
'Average year' 2011	205.4	18.2	27.9	2724.7	2845.3	+4.4%	*0.26*
'Wet year' 2012	407.4	18.5	28.2	4016.9	3994.9	-0.6%	0.36

3.5 Effect of soil water conservation on future climate scenarios

3.5.1 Climate data of the four climate scenarios in 2050

If SWC strategies can work as adaptation strategy towards climate change is tested by using four different climate scenarios for 2050. The predicted relative differences between the current weather conditions and future climate of these scenarios are used to simulate future climate for Makueni; for a dry-,wet- and average year, which resulted in 12 different climate scenarios. A summary of these simulations are shown in Table 12. The monthly variations in precipitation, minimum- and maximum temperatures for the short raining season are shown in Appendix VII.

In general, the temperature is expected to increase in all scenarios for the short raining season. Also precipitation increases in most cases, except for RCP 8.5. RCP8.5 is the most extreme scenario; the temperature increases and precipitation decreases the most in all simulations compared to the current weather conditions. More variation is observed regarding precipitation of the different scenarios. The minimum temperatures increases per scenario, whereas the maximum temperatures also seem to be more variable.

According to the IPCC (IPCC, 2011) more extreme weather conditions are predicted. It is not sure however, how often or in what intensity these events will occur. Therefore, these events could not be incorporated for the simulations. However, extreme weather events can eventually be very important for defining crop-failures. For instance, an increase in extreme rain events, can lead to more droughts due to a decrease in distribution of water supply.

Table 12. Summary of simulated future climate for short raining season in Makueni

Weather conditions and climate scenarios (2050)	Precipitation (mm)	Min. Temp	Max. Temp
	October-December	˚C	˚C
'Dry year'			
2007	131.2	20.5	28.0
RCP2.6	136.2	22.1	28.6
RCP4.5	148.4	22.5	29.3
RCP6.0	159.0	22.5	28.9
RCP8.5	97.3	23.2	29.5
'Average year'			
2011	205.4	18.2	27.9
RCP2.6	219.7	19.6	28.6
RCP4.5	204.4	20.0	29.2
RCP6.0	240.0	20.0	28.9
RCP8.5	178.6	20.6	29.4
'Wet year'			
2012	407.4	18.5	28.2
RCP2.6	644.6	20.0	28.9
RCP4.5	463.8	20.3	29.6
RCP6.0	483.6	20.3	29.2
RCP8.5	392.1	20.9	29.7

3.5.2 Intercropping and mono cropping fields

For all climate change scenarios in 2050, slightly higher yields are simulated for both the intercropping and mono cropping fields. However, the differences are not significant. It is therefore uncertain if intercropping can work as an adaptation strategy towards climate change. However, also here accounts that the nutrient-limited yields are not simulated. Bigger differences are expected if these simulations would be conducted.

Table 13. Simulation of water-limited yields of mono- and intercropping for 2050

Weather conditions and climate scenarios	Average yield (kg/ha)			
	Mono cropping	**Intercropping**	**Yield diff.**	*Sig.*
'Dry year'				
2007	2434.0	2481.9	+2.0%	0.16
RCP2.6	4549.4	4475.7	-1.6%	0.32
RCP4.5	4155.6	4156.8	0.0%	0.50
RCP6.0	4085.8	4109.8	+0.6%	0.42
RCP8.5	3707.1	3595.9	-3.0%	0.30
'Average year'				
2011	2424.7	2464.9	+1.7%	0.14
RCP2.6	3514.7	3533.4	+0.5%	0.39
RCP4.5	3020.5	3014.1	-0.2%	0.47
RCP6.0	3267.5	3309.5	+1.3%	0.19
RCP8.5	3088.1	3034.7	-1.7%	0.33
'Wet year'				
2012	6130.0	6184.4	+0.9%	0.13
RCP2.6	5529.7	5464.5	-1.2%	0.23
RCP4.5	5176.4	5184.0	+0.1%	0.19
RCP6.0	5237.3	5247.6	+0.2%	0.21
RCP8.5	4674.2	4674.4	0.0	0.17

3.5.3 Terraced and non-terraced fields

The simulations of water-limited yields for future climate scenarios resulted in bigger differences between the terraced and non-terraced fields (Table 14). The highest gain is observed in the scenarios in the dry year. In these scenarios the demand for water by plants is the highest. By applying terraces the difference between the demand and supply of water is smaller than without terraces. Therefore the yields are significantly higher in the terraced fields. This also accounts for scenario RCP 8.5 in the average year (Sig.=0.09). Compared to the other scenarios in the average year, the precipitation is the lowest but the yield increased significant.

There are no significant higher yields in the wet year by applying terraces. In fact, they remain relatively equal. The amount of precipitation is high enough to meet the demand of water-supply to plants and applying terraces seems unnecessary. This also accounts for RCP8.5 in the wet year.

Table 14. Simulation of water-limited yields of terraced and non-terraced fields for 2050

Weather conditions and climate scenarios	Average yield (kg/ha)			
	Non-terraced	Terraced	Yield diff.	*Sig.*
'Dry year'				
2007	1970.8	2964.6	+50.4%	**0.02**
RCP2.6	4673.3	5127.9	+9.7%	**0.01**
RCP4.5	4372.4	4743.2	+8.5%	**0.06**
RCP6.0	4358.8	4725.0	+8.4%	0.12
RCP8.5	3664.7	4168.4	+13.7%	**0.00**
'Average year'				
2011	2724.7	2845.3	+4.4%	0.26
RCP2.6	3905.5	3942.7	+1.0%	0.39
RCP4.5	3274.4	3342.2	+2.1%	0.23
RCP6.0	3628.0	3737.4	+3.0%	0.26
RCP8.5	3311.0	3435.5	+3.8%	**0.09**
'Wet year'				
2012	4016.9	3994.9	-0.6%	0.36
RCP2.6	5597.9	5597.4	0.0	0.44
RCP4.5	5275.5	5275.2	0.0	0.40
RCP6.0	5364.1	5363.0	0.0	0.39
RCP8.5	4715.0	4715.0	0.0	0.44

3.6 General discussion

SWC has been suggested by CCAFS as a climate adaptation strategy by alleviating worsening of soil conditions. Applying SWC has indeed positive effects on soil conditions in our study area. By intercropping legumes with maize higher nitrate levels can be found in the soil. Applying terraces results in higher contents of soil moisture. Although these SWC strategies are already broadly being applied in the study area, it opened great opportunities to study if these strategies indeed result in relatively better soil conditions by measuring soil properties in the field. The benefits of SWC strategies are often only observed after long periods of managing, which was the case in our study area. The long periods of farming under SWC strategies did not result in large differences for the other soil properties. However, it is uncertain if these small differences will become bigger in the future. Terracing for example, was mainly applied to minimize runoff and erosion and thereby preventing soil degradation. Lower levels of soil pH can indicate if this the case. Although there was no sign of soil degradation on the non-terraced fields in our study area, it is likely that this will happen eventually without applying terraces.

Improved soil conditions can result in an increase in crop production. Using a crop-growth simulation model made it possible to test this for the intercropping fields. For the terraced fields, runoff fractions were used. There was no increased production observed for the water-limited yields by applying intercropping. However, it is likely that higher yields are expected if the nutrient-limited yields would be simulated, because the nutrient levels in the soil on the intercropping fields were significantly higher. A larger supply of nutrients to the crops, eventually results in an increases of yields (Brady and Weil, 2004). Important to note however, is that by intercropping the relative amounts of maize production might decrease due to a lower available area of maize that can be planted. Crop density however, is not adjusted as input for this study.

By applying terraces, the water-limited yields were significantly higher under the current climate conditions for a dry year as well as for its four climate scenarios for 2050. This implies that by terracing, more resilience is created towards climate change and can indeed be considered as an adaptation strategy. However, it also implies that terracing is effective under current dry weather conditions. Although these are the results for our study area, applying terraces likely increases yields in many other areas. Especially in areas where droughts can play an important role in determining failures of rain-fed crops due to climate change.

Climate change can also affects pests and diseases. Both direct and indirect effects of moisture stress makes crops more vulnerable (Rosenzweig et al., 2001). Dry and wet conditions for example, likely increases infections of fungi for crops than when it is not stressed and can lead to an increase of crop failures. Pests and diseases are not incorporated in the WOFOST crop-growth model, which means that these effects cannot be observed in the different climate scenarios.

4. Conclusion

SWC strategies are promoted by CCAFS in order to overcome the threats to agriculture and food security in a changing climate. Terracing as SWC strategy forms a great potential as adaptation strategy towards climate change. In both current dry weather conditions as well as in future climate change scenarios for dry weather conditions in 2050, the water-limited yields were significantly higher by applying terraces. This implies that terracing is not only a great potential as adaptation strategy for climate change but also increases yields under current climate conditions.
Intercropping as SWC strategy had no significant effect on water-limited yields. For both current climate conditions as well as future climate scenarios, yields did not increase by intercropping.

SWC also improved soil conditions, where:

- Intercropping increased nitrate levels in the soil,
- Soil moisture was higher on the terraced fields.

Applying SWC strategies as promoted by CCAFS indeed improves soil conditions and terracing contributes as an adaptation towards climate change. Therefore continuing with stimulating farmers to apply such strategies –as done by CCAFS- can decrease threats to agriculture and food security in a changing climate. Increased water-limited yields by applying terraces makes farmers less vulnerable towards climate change and more food secure. Applying intercropping as SWC strategy likely has positive effects as well. However, the nutrient-limited yields should be evaluated in order to confirm this.

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At last I want to thank my (Wageningen)family for their great support. Maricke, thanks for the great laughs and sharing of awkward moments at the coffee machine. Lotte, Iris and Laura, thank your mental support, breakfast, dinners etc. in Gaia. I owe you big time.

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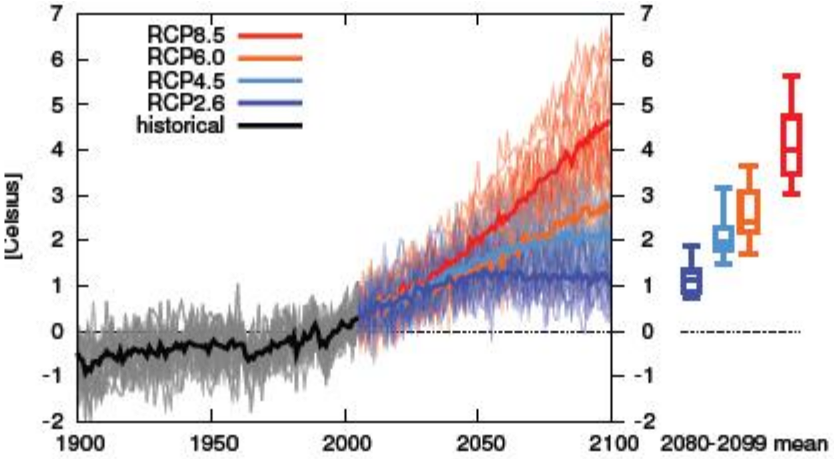
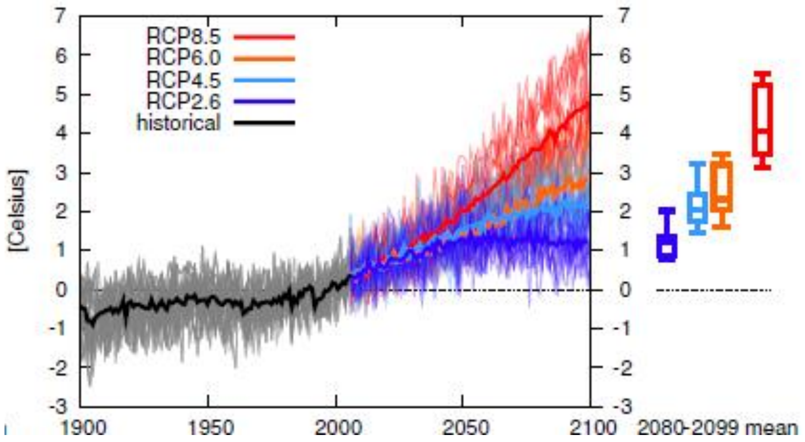
Appendices

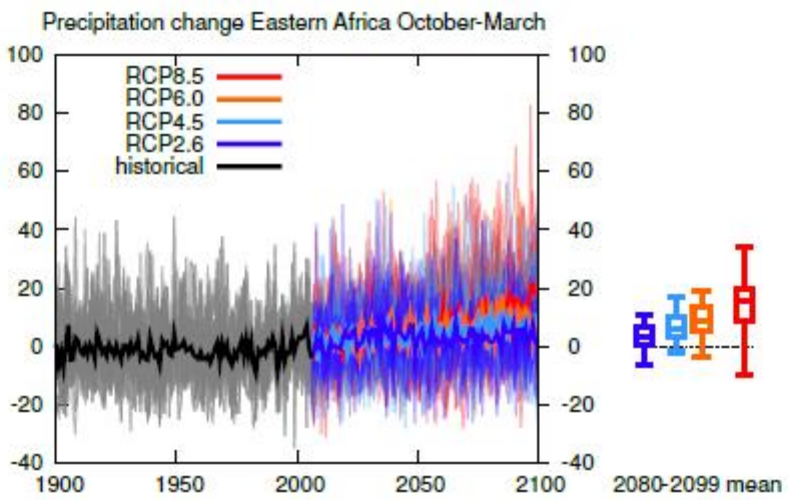
Appendix I



Appendix I-Figure 1. Temperature change October-November Eastern Africa (IPCC)



Appendix I-Figure 2. Temperature change December-February Eastern Africa (IPCC,2011)



Appendix I-Figure 3. Precipitation change short raining season in Eastern Africa (IPCC,2011)

Appendix II

The backward method is used in order to estimate the model parameters for the texture analysis. The input variables for this model were: NTU measurements after 1 hour, and 40 seconds (see 2.7) and clay% and sand%; the parameters of clay% and sand% are the results of laboratory analyses and therefore used for calibration of the model. The square root and exponential power of two of both NTUs were also used as well as the interaction (NTU 1h*NTU 40s). In Table 1 and 2, the outputs are shown for sand and clay. In Table 1 is shown that after eliminating four variables, the R^2 remains relatively stable (R^2=0.445). In the first place, one would chose four step four, however, implementing this formula lead to negative values. Therefore, step five is used to predict the sand percentage.

Appendix II-Table 1. Summary of backward method results for estimating equation to model sand (left) and model equation (right)

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.696[a]	0.484	0.156	7.79
2	.695[b]	0.484	0.225	7.46
3	.695[c]	0.483	0.285	7.17
4	.694[d]	0.482	0.333	6.92
5	.667[e]	0.445	0.334	6.92
6	.663[f]	0.439	0.369	6.73

5	(Constant)	103.285
	(NTU)40sec2	0
	(NTU) √40sec	-1.538
	(NTU40sec*1hr	0

Appendix II-Table 2.Summary of backward method results for estimating equation to model sand clay (left) and model equation (right)

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.763a	0.582	0.315	6.01
2	.762b	0.581	0.372	5.76
3	.760c	0.578	0.415	5.55
4	.754d	0.569	0.446	5.40
5	.723e	0.523	0.427	5.50
6	.710f	0.503	0.441	5.43

5	(Constant)	-0.099
	(NTU)40sec2	0
	(NTU) √40sec	1.163
	(NTU40sec*1hr	0

Appendix II-Table 3. Results of the backward method for sand

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	116.535	101.707		1.146	0.276
	NTU40	0.1	0.748	2.798	0.134	0.896
	NTU1h	-0.258	2.268	-1.278	-0.114	0.911
	Exp40	-7.19E-05	0	-2.123	-0.291	0.776
	Root40	-4.738	21.345	-3.068	-0.222	0.828
	Exp1h	-0.001	0.004	-0.818	-0.208	0.839
	Root1h	3.898	29.057	1.071	0.134	0.896
	NTU40NTU1	0.001	0.001	2.891	1.226	0.246
2	(Constant)	113.201	93.301		1.213	0.248
	NTU40	0.043	0.528	1.192	0.081	0.937
	Exp40	-5.40E-05	0	-1.593	-0.297	0.772
	Root40	-2.985	14.146	-1.933	-0.211	0.836
	Exp1h	-0.001	0.002	-1.226	-0.807	0.436
	Root1h	0.61	2.821	0.168	0.216	0.832
	NTU40NTU1	0.001	0.001	2.861	1.274	0.227
3	(Constant)	105.794	17.893		5.913	0
	Exp40	-3.96E-05	0	-1.17	-0.998	0.336
	Root40	-1.845	1.417	-1.195	-1.302	0.215
	Exp1h	-0.001	0.001	-1.245	-0.863	0.404
	Root1h	0.502	2.385	0.138	0.21	0.837
	NTU40NTU1	0.001	0	2.939	1.511	0.155
4	(Constant)	106.336	17.091		6.222	0
	Exp40	-3.93E-05	0	-1.159	-1.026	0.322
	Root40	-1.67	1.108	-1.082	-1.508	0.154
	Exp1h	-0.001	0.001	-1.046	-0.994	0.337
	NTU40NTU1	0.001	0	2.784	1.602	0.131
5	(Constant)	103.285	16.806		6.146	0
	Exp40	0	0	-0.264	-0.387	0.704
	Root40	-1.538	1.099	-0.996	-1.399	0.182
	NTU40NTU1	0	0	1.096	3.031	0.008
6	(Constant)	108.74	8.901		12.216	0
	Root40	-1.906	0.539	-1.234	-3.537	0.003
	NTU40NTU1	0	0	1.078	3.089	0.007

Appendix II-Table 4. Results of the backward method for clay

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	-21.396	78.457		-0.273	0.79
	NTU40	-0.063	0.577	-2.057	-0.109	0.915
	NTU1h	-0.324	1.75	-1.873	-0.185	0.857
	Exp40	6.71E-05	0	2.312	0.352	0.731
	Root40	3.009	16.466	2.275	0.183	0.858
	Exp1h	0.002	0.003	2.112	0.598	0.562
	Root1h	2.907	22.414	0.933	0.13	0.899
	NTU40NTU1	-0.001	0	-3.071	-1.446	0.176
2	(Constant)	-13.79	34.891		-0.395	0.7
	NTU1h	-0.454	1.234	-2.623	-0.368	0.72
	Exp40	4.66E-05	0	1.605	1.431	0.178
	Root40	1.215	1.539	0.919	0.79	0.445
	Exp1h	0.002	0.002	2.369	0.938	0.367
	Root1h	4.646	15.143	1.491	0.307	0.764
	NTU40NTU1	-0.001	0	-3.127	-1.583	0.139
3	(Constant)	-4.032	13.839		-0.291	0.775
	NTU1h	-7.80E-02	0.15	-0.451	-0.518	0.613
	Exp40	4.46E-05	0	1.537	1.449	0.171
	Root40	1.556	1.025	1.177	1.518	0.153
	Exp1h	0.001	0.001	1.754	1.183	0.258
	NTU40NTU1	-0.001	0	-3.385	-1.964	0.071
4	(Constant)	-3.047	13.345		-0.228	0.823
	Exp40	4.35E-05	0	1.499	1.455	0.168
	Root40	1.291	0.865	0.976	1.492	0.158
	Exp1h	0.001	0.001	1.18	1.229	0.239
	NTU40NTU1	-0.001	0	-3.09	-1.95	0.071
5	(Constant)	-0.099	13.349		-0.007	0.994
	Exp40	1.42E-05	0	0.489	0.774	0.451
	Root40	1.163	0.873	0.88	1.332	0.203
	NTU40NTU1	0	0	-1.185	-3.534	0.003
6	(Constant)	-8.763	7.175		-1.221	0.24
	Root40	1.747	0.434	1.321	4.022	0.001
	NTU40NTU1	0	0	-1.152	-3.509	0.003

Appendix III

Below, the couples are shown of the terraced/non-terraced fields and for the mono-/intercropping fields.

Appendix III-Table 1. Couples of the terraced and non-terraced fields.

	1		2		3		4	
Terraced	No	Yes	No	Yes	No	Yes	No	Yes
Slope	22	18	13	15	10	10	9	12
Clay (%)	23.5	31.3	23.3	20.5	29.1	20.4	28.5	17.4
Sand (%)	70.7	60.0	71.0	62.3	63.0	75.0	63.8	79.2
Terraced since	-	1975	-	1990	-	2003	-	2008
Maintained	-	Well	-	Average	-	Well	-	Well
Last time manured	Never	1 month	Never	6 months	Never	No	Never	1 month

	5		6		7		8	
Terraced	No	Yes	No	Yes	No	Yes	No	Yes
Slope	11	8	10	10	8	8	9	9
Clay (%)	27.8	20.1	21.3	31.9	25.1	29.3	23.6	22.8
Sand (%)	64.8	75.5	73.7	59.2	68.5	62.8	70.6	71.7
Terraced since	-	1963	-	2003	-	1994	-	2004
Maintained	-	Well	-	Average	-	Average	-	Well
Last time manured	Never	6 months	Never	36 months	Never	6 months	Never	Never

	9		10		11	
Terraced	No	Yes	No	Yes	No	Yes
Slope	22	25	7	7	40	35
Clay (%)	33.8	29.5	26.5	24.8	30.3	N/A
Sand (%)	56.6	62.4	66.6	69.0	61.3	N/A
Terraced since		2005	-	1950	-	2004
Maintained	-	Well	-	Well	-	Average
Last time manured	Never	Never	Never	24 months	Never	Never

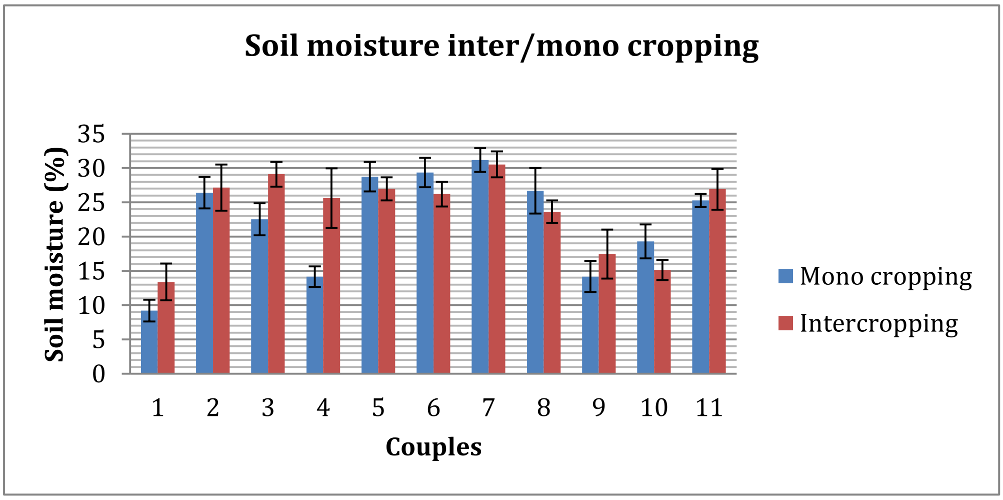
Appendix II-Table 5. Couples for intercropping and mono cropping

	1		2		3		4	
Cropping	Mono	Inter	Mono	Inter	Mono	Inter	Mono	Inter
Since	1980	1980	1963	1963	2008	2008	2012	2012
Clay(%)	32.4	30.8	17.6	22.3	22.1	24.9	25.8	25.1
Sand(%)	58.6	60.7	79.0	72.4	72.7	68.9	67.6	68.6
Last time manured	12 months	12 months	6 months	0 months	Never	0 months	Never	Never

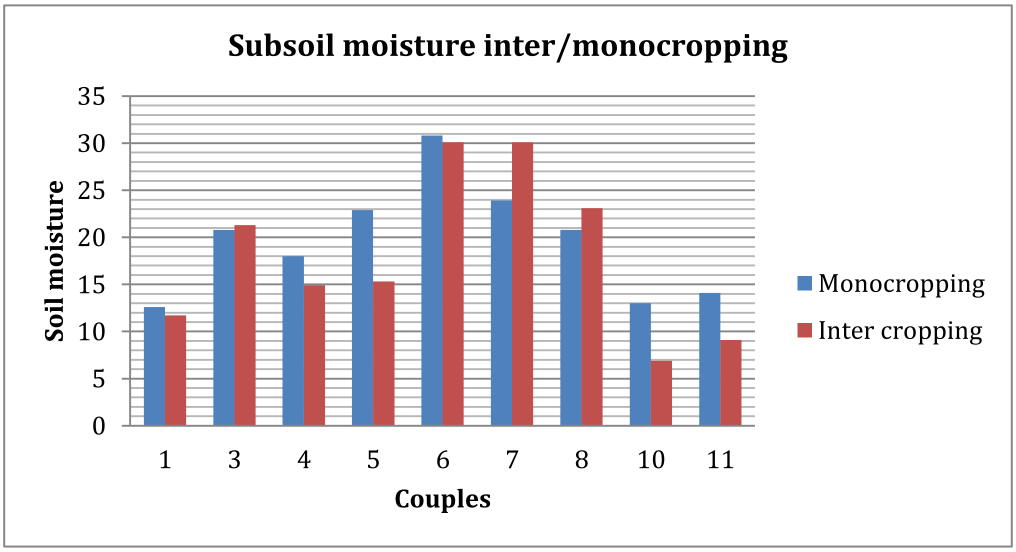
	5		6		7		8	
Cropping	Mono	Inter	Mono	Inter	Mono	Inter	Mono	Inter
Since	1990	1990	2009	1990	2009	1990	2011	2011
Clay(%)	20.6	11.1	36.6	74.7	11.7	32.2	23.2	32.2
Sand(%)	74.7	87.8	65.2	27.5	87.0	58.8	71.1	58.8
Last time manured	Never	Never	0 months	0 months	0 (F)	Never	0 months	0 months

Cropping	11		12		13	
Since	Mono	Inter	Mono	Inter	Mono	Inter
Clay(%)	1990	1990	1970	1970	2011	1992
Sand(%)	21.1	21.5	22.8	27.6	30.3	36.7
Crop rotation	74.1	73.5	71.7	65.1	61.4	52.6
Last time manured	Never	Never	Never	Never	36 months	24 months

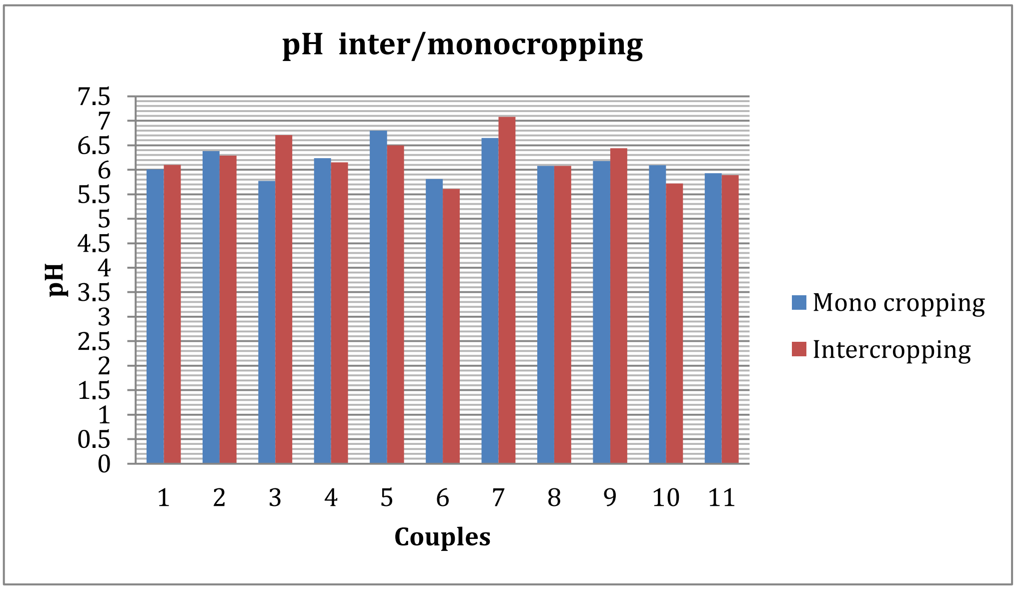
Appendix IV



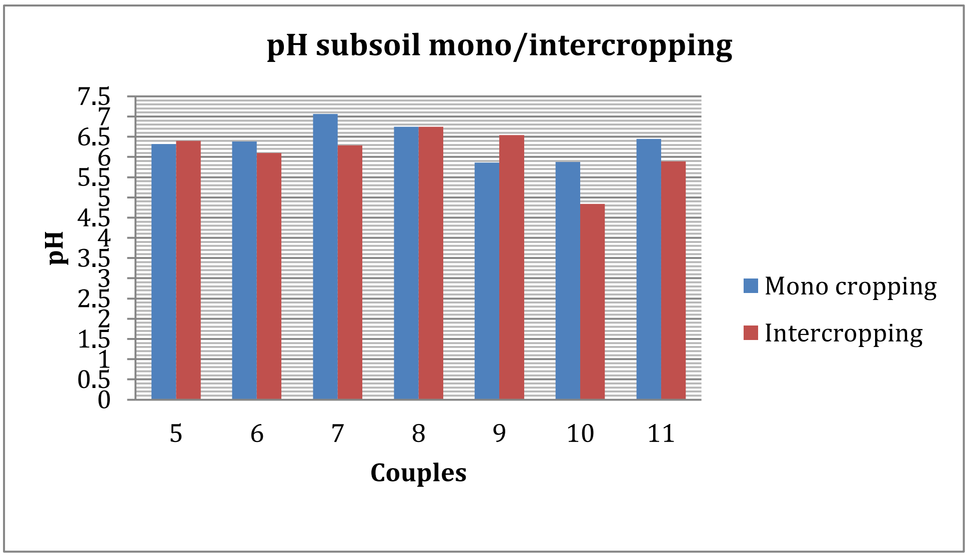
Appendix IV- Figure 1. Soil moisture of the topsoil of the intercropping and mono cropping fields.



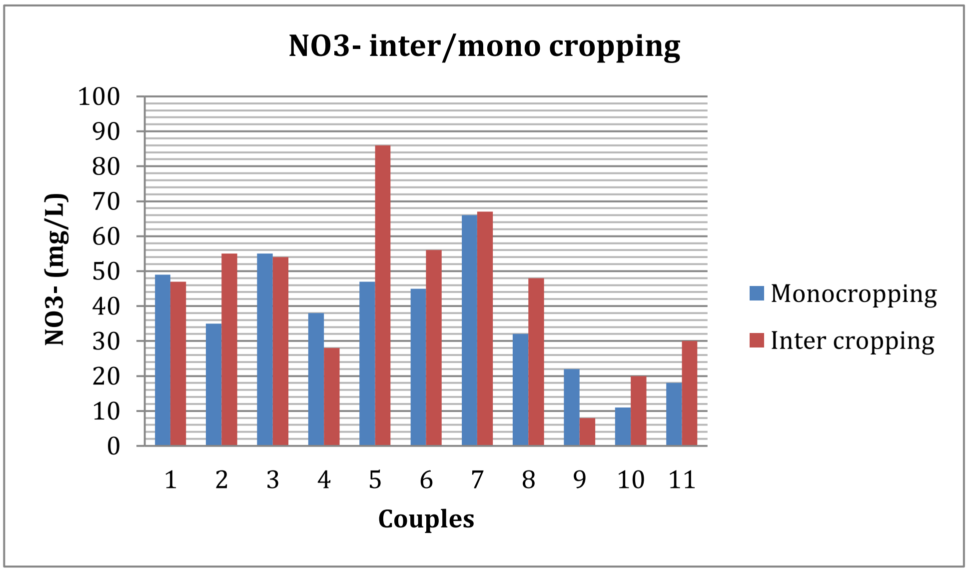
Appendix IV- Figure 2.Soil moisture of the subsoil of the intercropping and mono cropping fields.



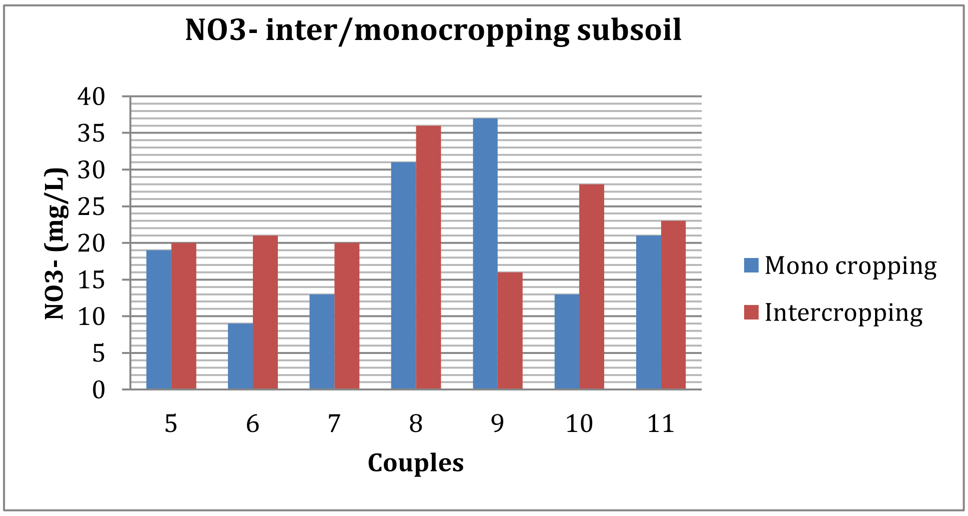
Appendix IV- Figure 3. pH of topsoil of the intercropping and mono cropping fields.



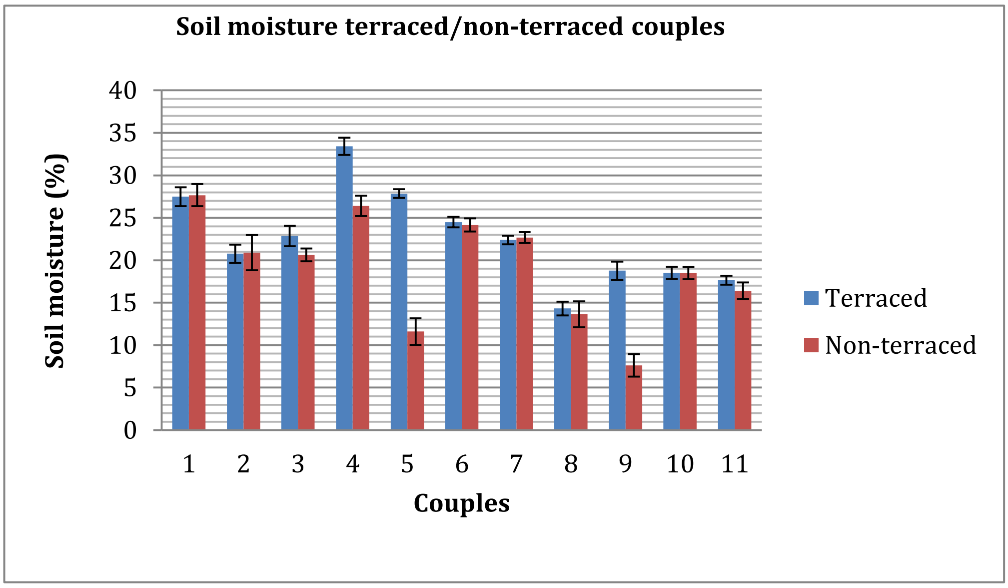
Appendix IV- Figure 4. pH of the subsoil of the intercropping and mono cropping fields.



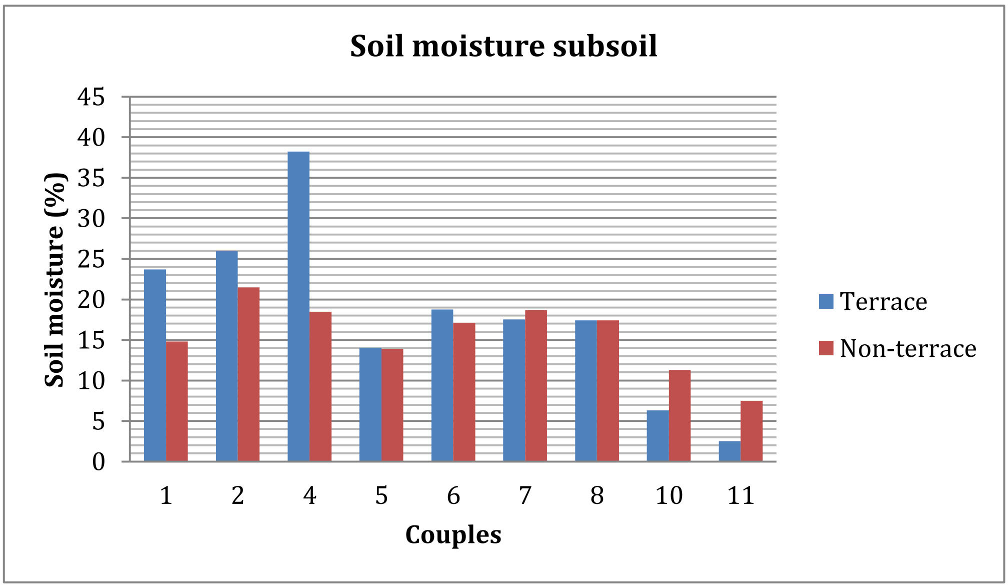
Appendix IV- Figure 5. Nitrate levels of the topsoil of the intercropping and mono cropping fields.



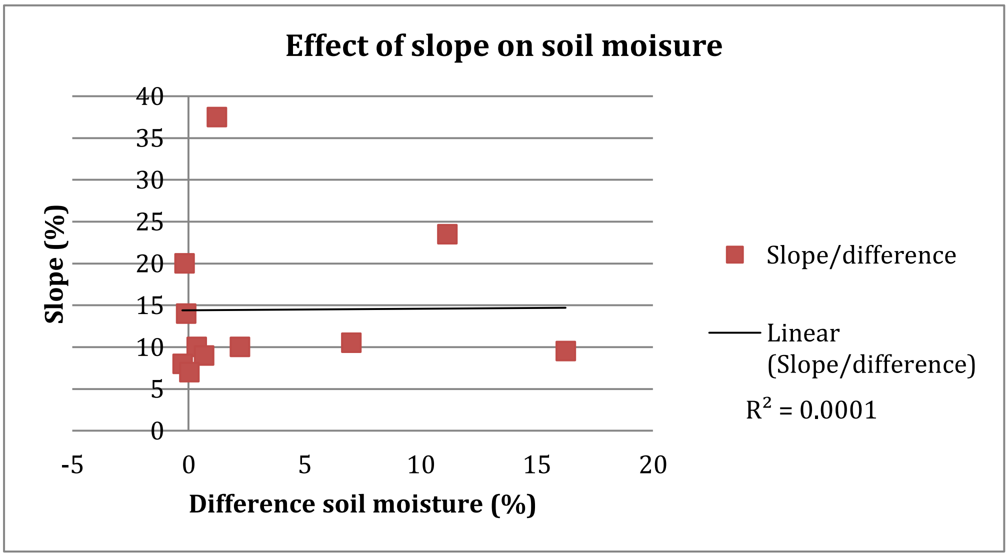
Appendix IV- Figure 6. Nitrate levels of the subsoil of the intercropping and mono cropping fields.



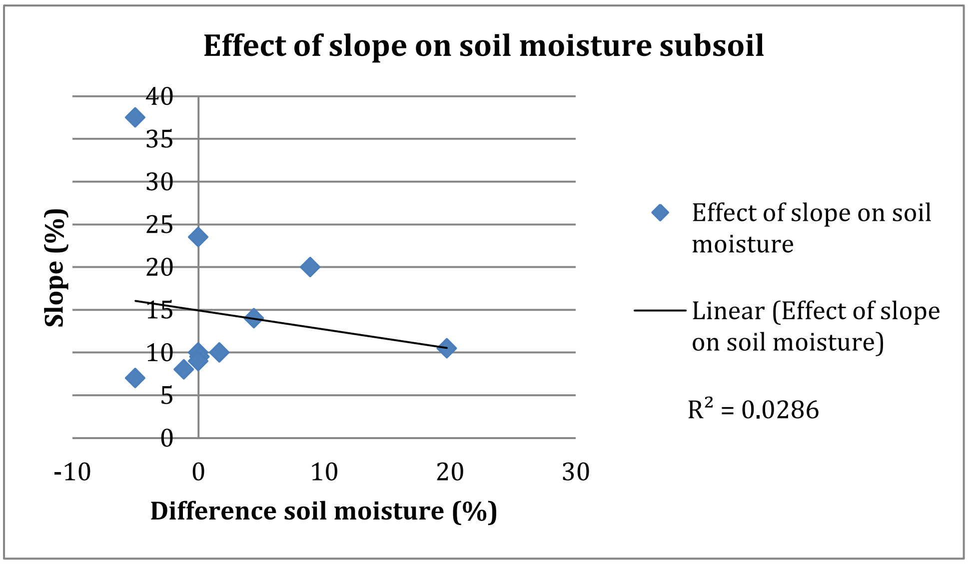
Appendix IV- Figure 7. Soil moisture of the topsoil of the terraced and non-terraced fields



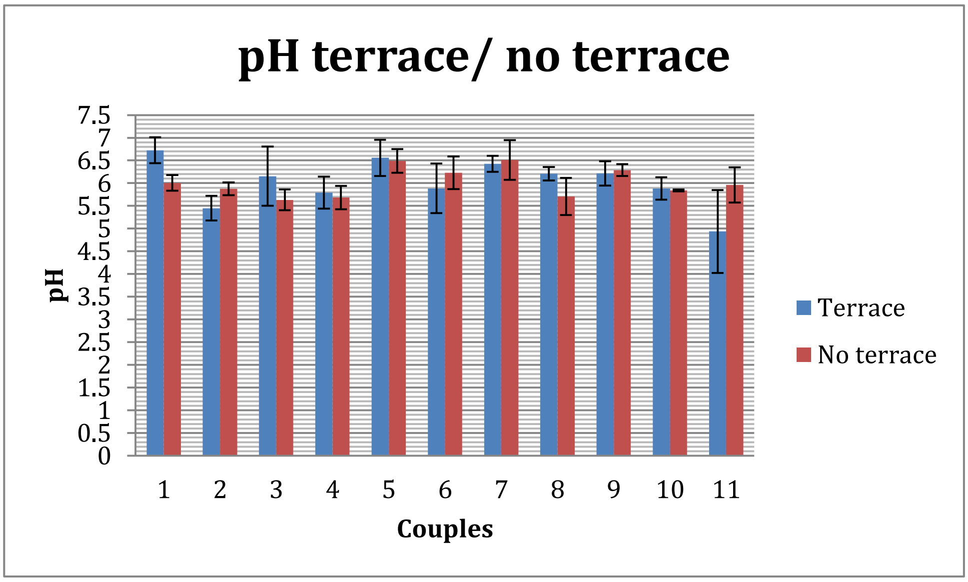
Appendix IV- Figure 8. Soil moisture of the subsoil of the terraced and non-terraced fields



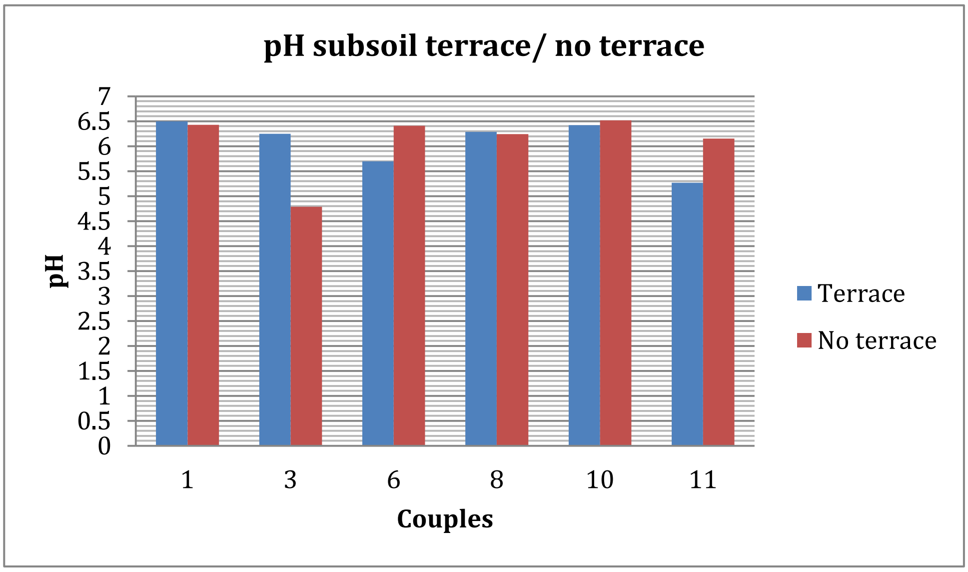
Appendix IV- Figure 9. Effect of slope on soil moisture



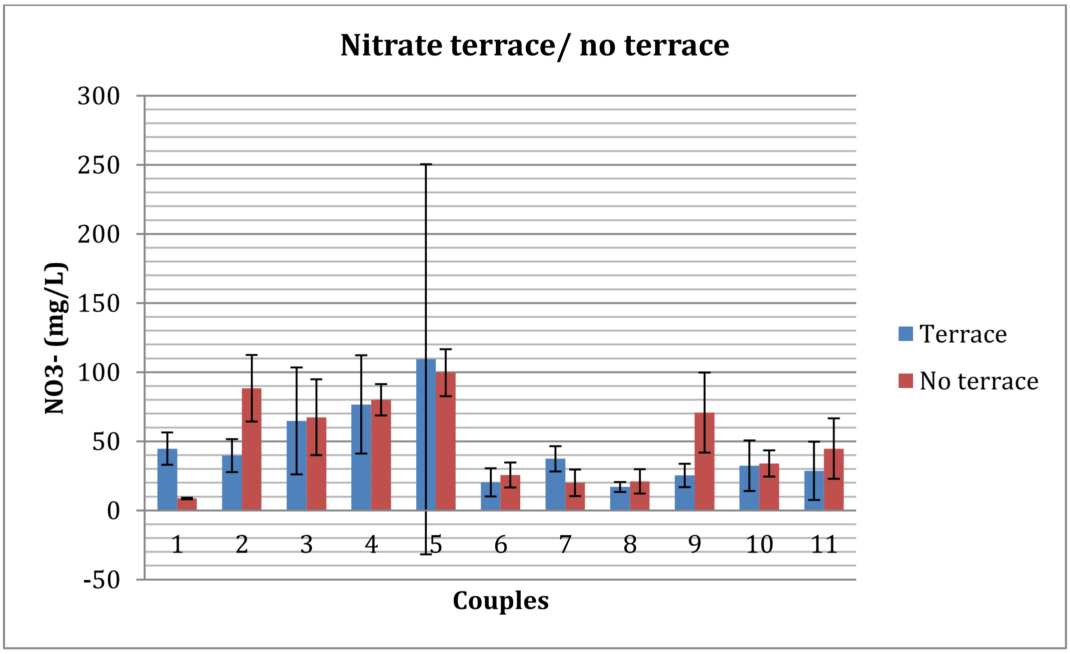
Appendix IV- Figure 10. Effect of slope on soil moisture subsoil



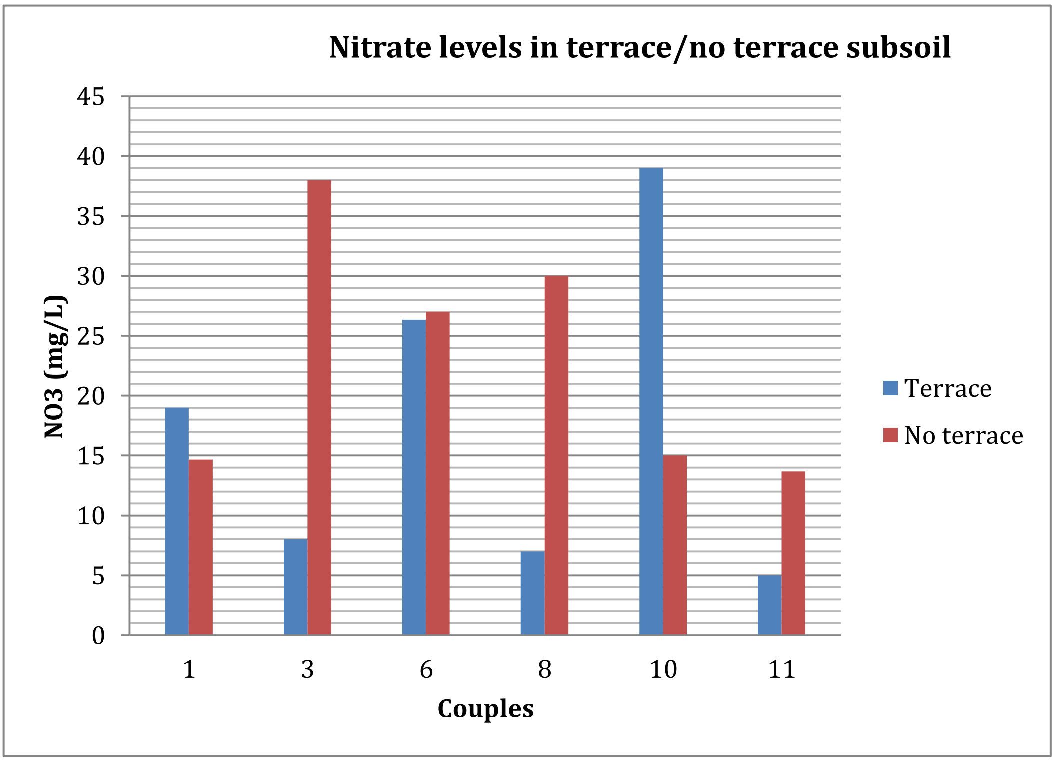
Appendix IV- Figure 11. pH of the topsoil of the terraced and non-terraced fields



Appendix IV- Figure 12. pH of the subsoil of the terraced and non-terraced fields

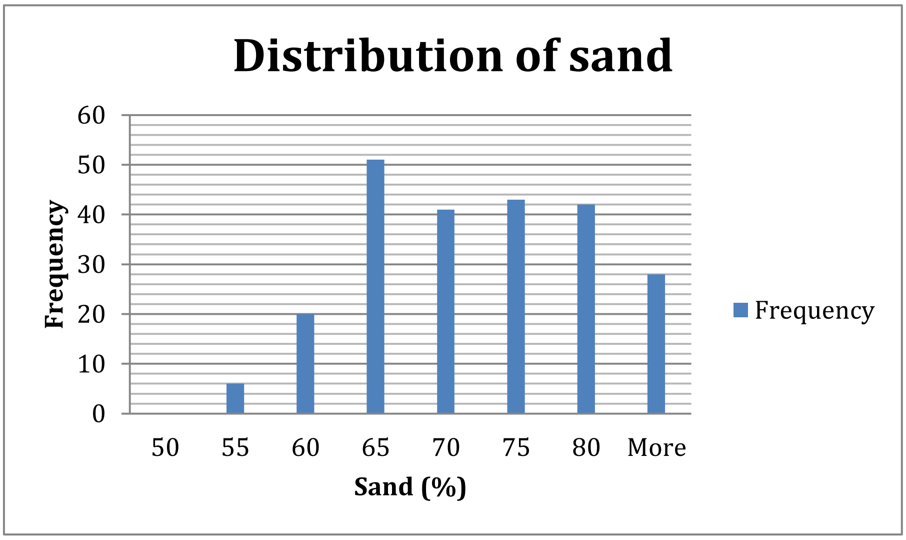


Appendix IV- Figure 13. Nitrate levels of the topsoil of the terraced and non-terraced fields

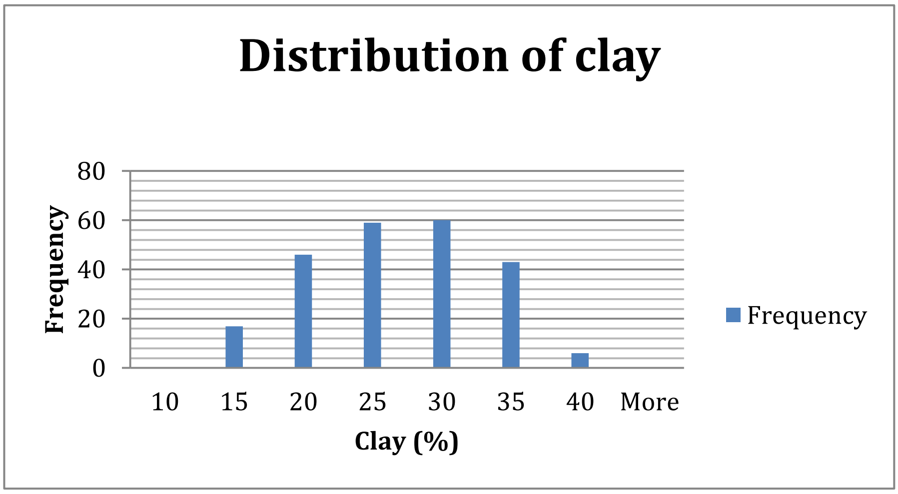


Appendix IV- Figure 14. Nitrate levels of the subsoil Nitrate levels of the topsoil of the terraced and non-terraced fields

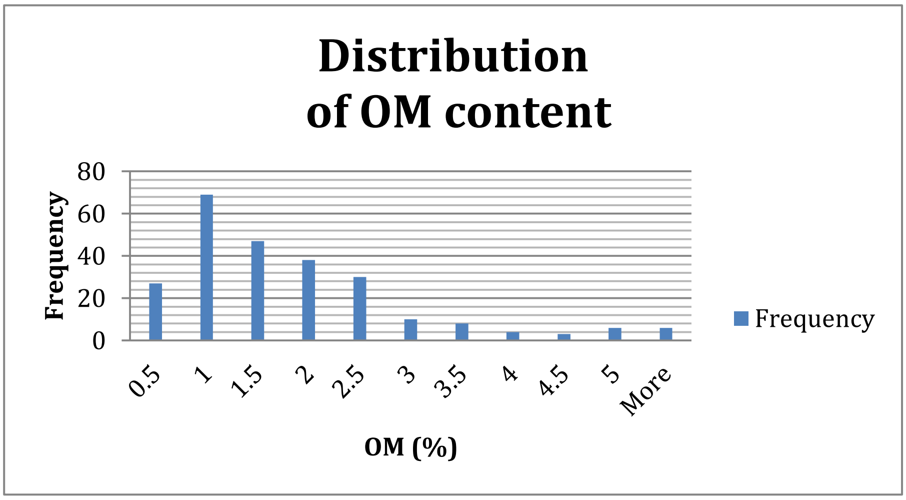
Appendix V



Appendix V-Figure 1. Distribution of sand percentage (%)



Appendix V-Figure 2. Distribution of clay



Appendix V-Figure 3. Distribution of OM (%)

Appendix VI

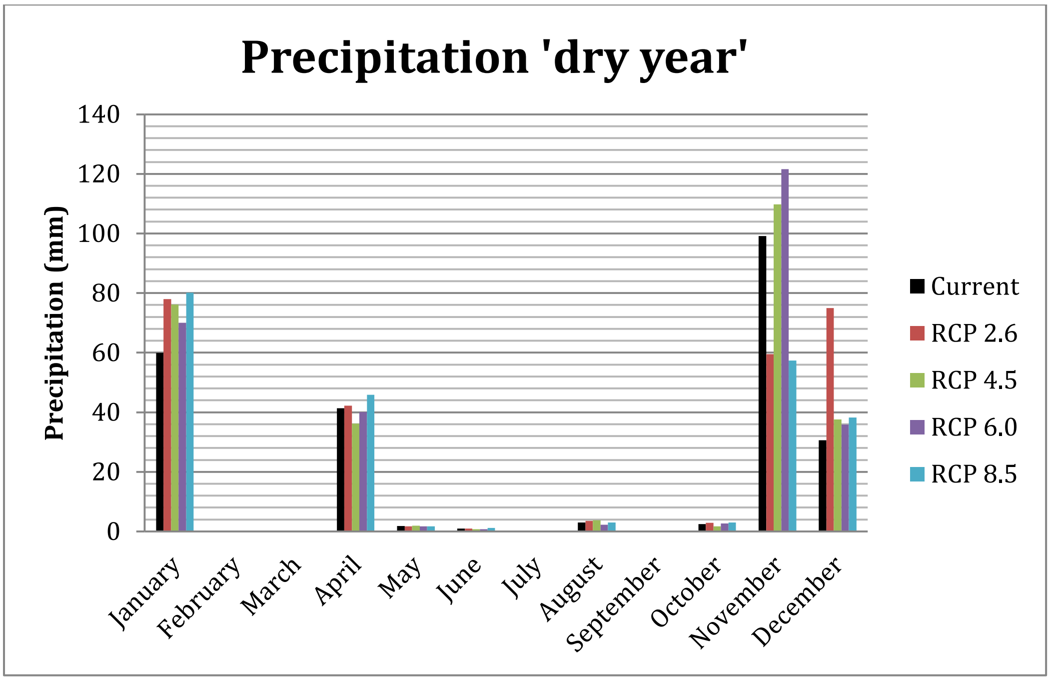
Appendix VI-Table 1. Results of field capacities for inputs in WOFOST

	Mono cropping		Intercropping	
Couple	OM (%)	Moisture content at Field capacities (v%)	OM (%)	Moisture content at Field capacities (%)
1	1.3	0.300	1.7	0.303
2	1.2	0.175	2.0	0.184
3	2.0	0.222	1.9	0.222
4	1.4	0.247	1.0	0.243
5	1.7	0.207	3.1	0.224
6	1.6	0.334	2.0	0.337
7	2.4	0.140	2.4	0.140
8	1.1	0.223	1.7	0.229
9	0.8	0.200	0.3	0.194
10	0.4	0.211	0.7	0.214
11	0.6	0.277	1.1	0.281

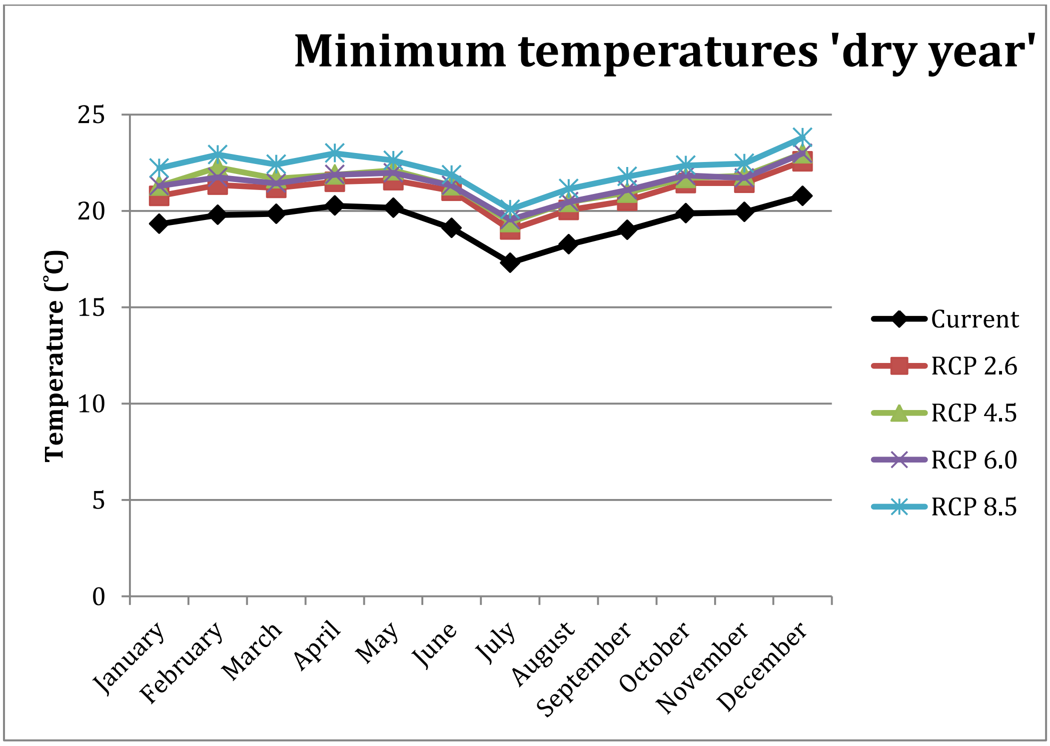
Appendix VI-Table 2. Inputs for field capacities and runoff fractions for WOFOST model

	Terraced			Non-terraced		
Couple	Slope(%)	Runoff fraction	Moisture content at Field capacities (v%)	Slope(%)	Runoff fractions	Moisture content at Field capacities (%)
1	-	-	0.327	22	0.200	0.216
2	-	-	0.279	13	0.200	0.246
3	-	-	0.213	10	0.133	0.284
4	-	-	0.193	9	0.133	0.284
5	-	-	0.234	11	0.200	0.286
6	-	-	0.291	10	0.133	0.203
7	-	-	0.275	8	0.133	0.234
8	-	-	0.213	9	0.133	0.221
9	-	-	0.276	22	0.200	0.321
10	-	-	0.236	7	0.133	0.252
11	-	-	0.279	40	0.200	0.279

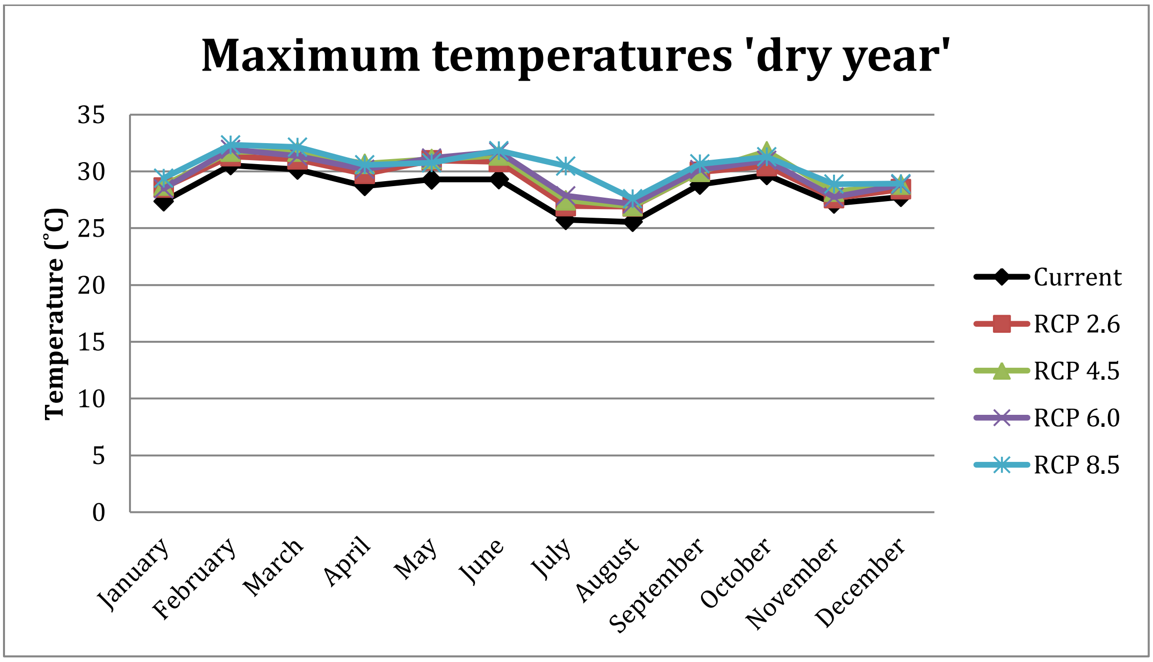
Appendix VII



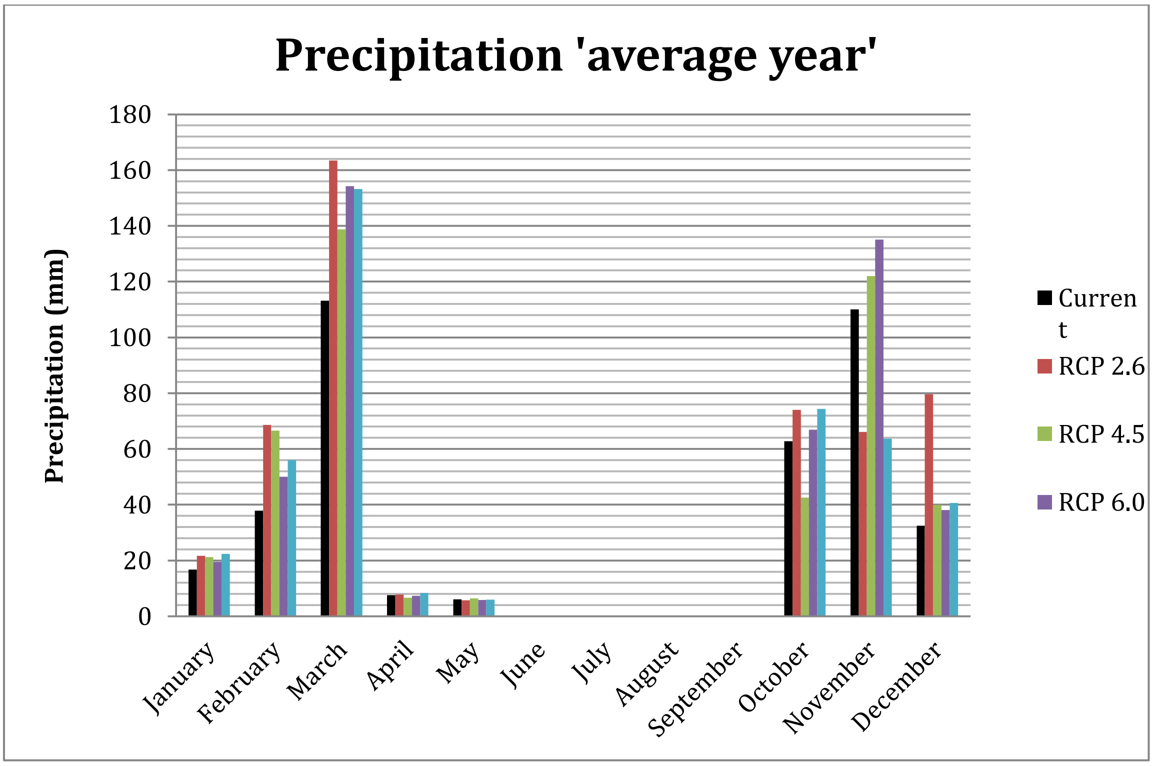
Appendix VII-Figure 1. Monthly information of change in precipitation, dry year.



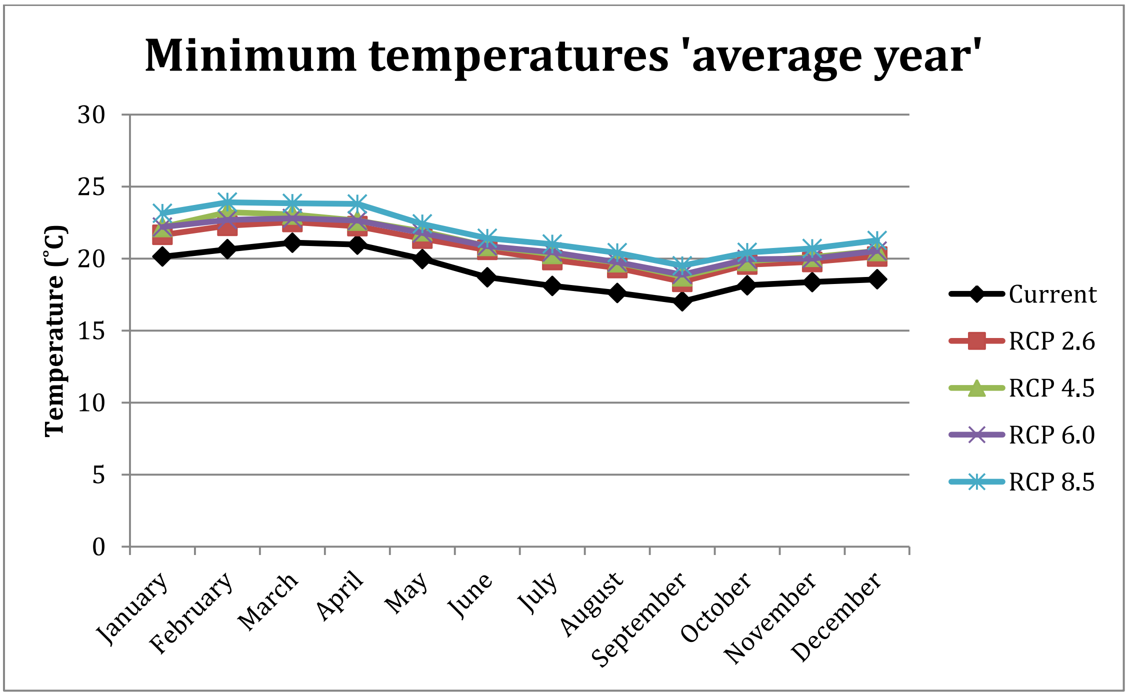
Appendix VII-Figure 2. Monthly information of change in minimum temperature, dry year.



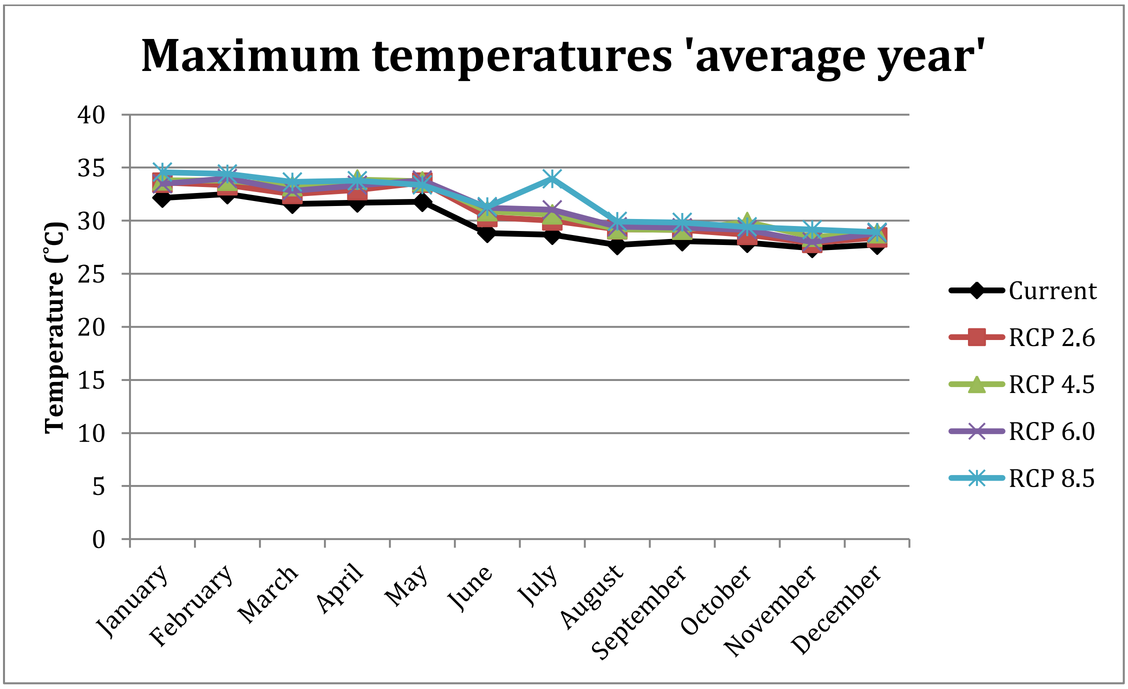
Appendix VII-Figure 3. Monthly information of change in maximum temperature, dry year.



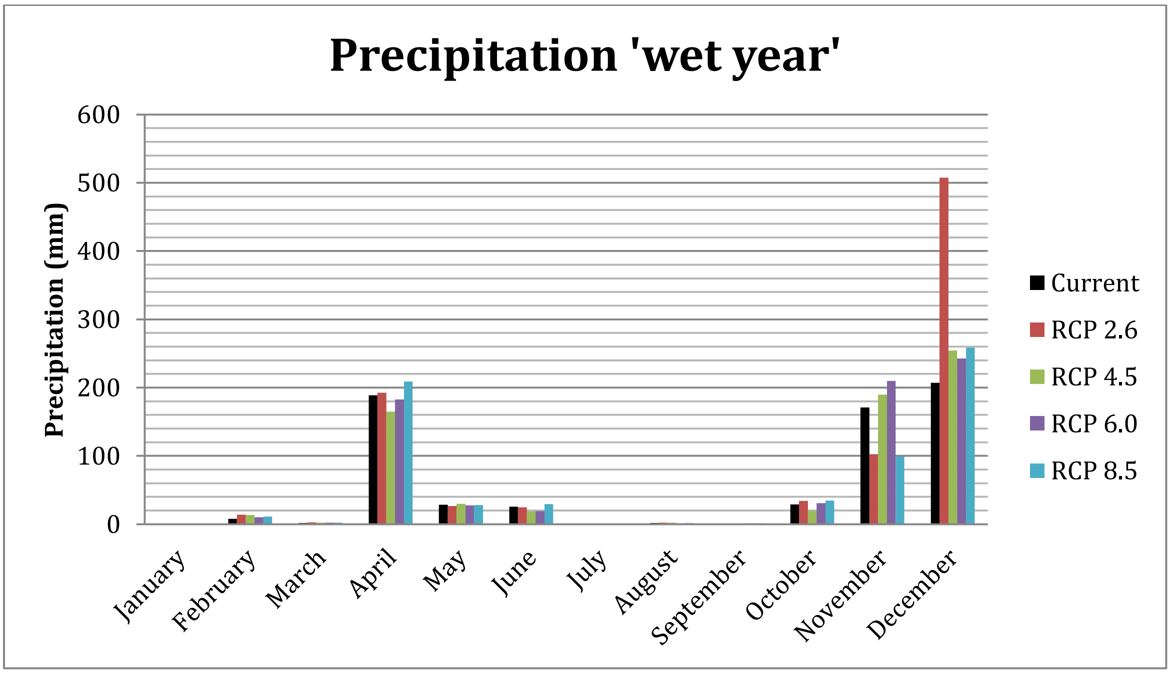
Appendix VII-Figure 4. Monthly information of change in precipitation, average year.



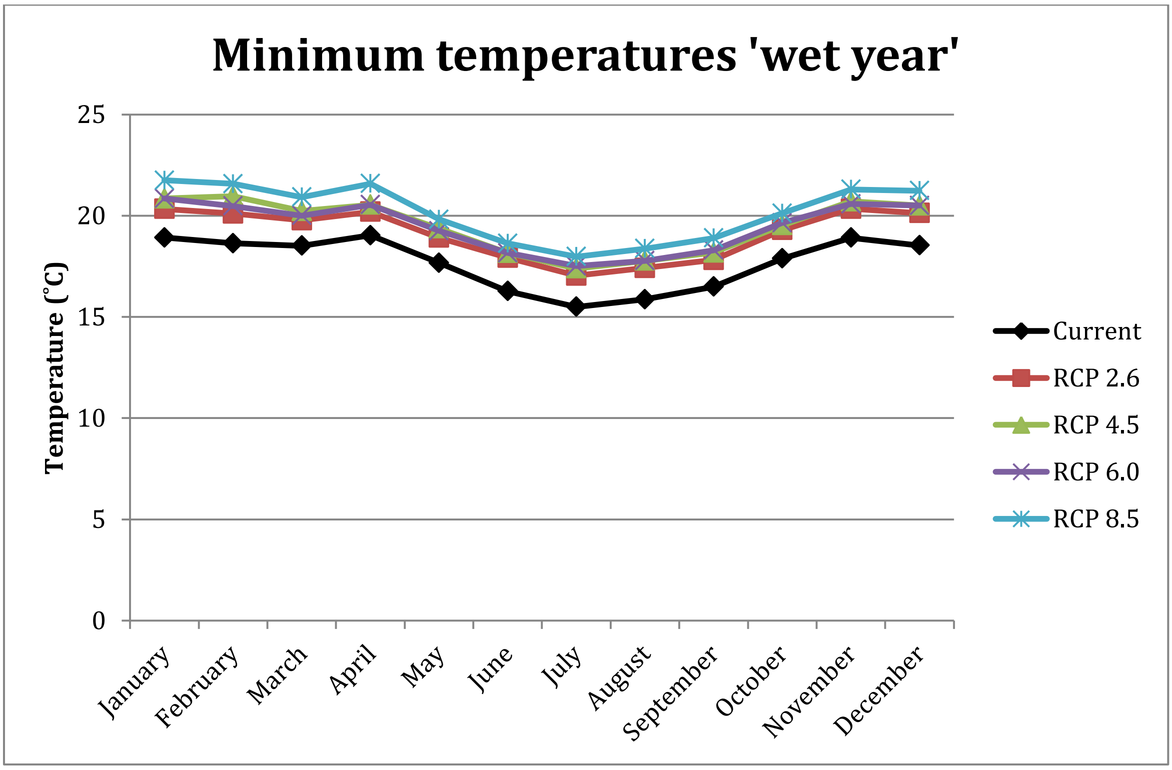
Appendix VII-Figure 5. Monthly information of change in minimum temperature, average year.



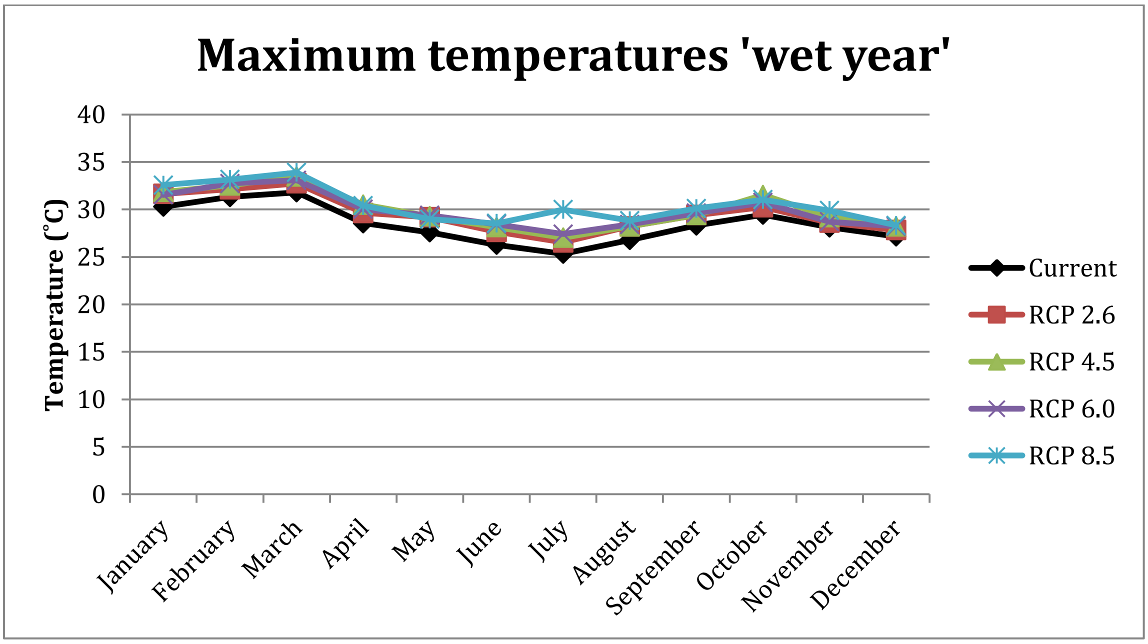
Appendix VII-Figure 6. Monthly information of change in maximum temperature, average year.



Appendix VII-Figure 7. Monthly information of change in precipitation wet year.



Appendix VII-Figure 8.. Monthly information of change in minimum temperature, wet year.



Appendix VII-Figure 9. Monthly information of change in maximum temperature, dry year.