Long-term effects of organic and mineral fertilizer application on physical soil properties and maize yield in western Kenya

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Abstract

To evaluate the effects of long-term application of organic and mineral fertilizers on maize yield and soil properties and further to investigate differences in soil fertility gradients, the Tropical Soil Biology and Fertility Institute of the International Centre for Tropical Agriculture (TSBF-CIAT) conducted an 8-year experiment on 12 farms in the districts Nyalgunga, Nyabeda and Vihiga in the Western Province of Kenya. The study was designed as a split plot model where each farm was split into high and low fertility plots on which the following treatments were applied: T2 – no fertilizer application (control), T4 – application of farmyard manure (FYM) alone and T5 – combined application of FYM, Mavuno fertilizer and top dressing. In scope of this thesis the physical soil properties such as bulk density (BD), soil texture , infiltration rate (IF) and aggregate stability (AS) as well as the soil organic carbon content in the soil (OC) were determined. Further Crop Evapotranspiration (ETc) and Water use efficiency were analyzed.

The ETc, varied between 2.34 and 4.84 mm/day and was highest during the development and late stage of the growing season. The rainfall was able to cover the water crop requirements of maize in all locations. Maize yield was highest at T5, followed by T4 and T2. Further, yield was strongly affected by the clay content and soil type and resulted in significant differences between the locations (Nyalgunga > Nyabeda > Vihiga). Other physical soil parameters (IF, BD, AS) did not influenced the maize yield. IF varied between 1.3 and 9.1m/day. BD was generally low with an overall mean of 1.16 g/cm³. The Aggregate stability was widely ranged and significantly higher in Nyabeda and on T4. OC was significantly higher on T5. The results indicated that mineral fertilizers contribute more to the increase of OC than organic fertilizers and that OC might not be the main driver of aggregation in tropical soils. AS seemed to be positive affected by organic fertilizers but IF and BD were not influenced by, nether organic or inorganic fertilizers. The results did not indicate any differences between high and low fertility plots, nether in maize yield nor in any of the physical soil properties.

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List of Acronyms

AEZ	Agro-ecological zone
AS	Aggregate stability in % by weight
BD	Bulk density in g/cm³
CIAT	International Centre for Tropical Agriculture
ETc	Crop Evapotranspiration in mm/day
ETo	Reference Evapotranspiration in mm/day
FAO	Food and Agriculture Organization of the United Nations
FYM	Farmyard manure
H	Plots with high fertility level
HAC	High activity clay
IF	Infiltration rate in cm/min
IR	Imazapyr resistant maize
ISFM	Integrated soil fertility management
K	Potassium
Kc	Single crop coefficient
L	Plots with low fertility level
LAC	Low activity clay
LM	Local maize
LR	Long rainy seasons
MAV	Mavuno fertilizer
N	Nitrogen
OC	Organic Carbon content in soil in % by weight
P	Phosphorus
RH	Relative humidity in %
SOM	Soil organic matter
SR	Short rainy seasons
SSA	Sub-Saharan Africa
T2	Control plot (no additional fertilizer application)
T4	Plot fertilized by FYM only
T5	Plot fertilized by FYM, MAV and TD
TD	Top dressing
TSBF	Tropical Soil Biology and Fertility Institute
u	Wind speed in m/s

1. Introduction

Soil fertility is noted as a crucial problem facing agricultural development and food security in Sub-Saharan Africa (SSA) (Sanchez 2002). The original fertile soils of the highlands of western Kenya enhanced settlement and lead to a rapid population growth in this region (Shepherd and Soule, 1998). The increase in rural population density and hence increase in land-use intensity are causing a negative nutrient balance among smallholder farms in SSA (Drechsel et al., 2001). Further, low organic matter, moisture stress and high erodibility are contributing to poor soil conditions (CIAT/TSBF/ICRAF, 2002).

Integrated soil fertility management (ISFM) is a holistic approach, including biological, physical, chemical, social, economical and political factors (CIAT/TSBF/ICRAF, 2002) to enhance agricultural productivity and hence to face problems related to poor soil fertility. This approach is generally accepted by development programs in SSA, and even more important, by the smallholder farmers themself (Place et al., 2003). The implementation of ISFM includes the utilization of available resources and the combination of organic and inorganic fertilizers (Vanlauwe, 2004)

Maize is an important crop in developing countries and it is expected that its demand will double by 2050 (Rosegrant et al., 2008). In Kenya, maize is accounting to approximately 35% of the consumed calories (FAOSTAT, 2010). Besides the decreasing soil fertility, the weed *Striga spp* and the stemborer are affecting maize production (Odendo et al., 2001). Tittonell et al. (2005) observed that the average grain production in western Kenya was as little as 1 tone per hectare and year. Further, farms with low resources endowment showed an average grain yield below annual family requirements.

A peculiarity of the soils in western Kenya is the heterogeneity in soil fertility at regional, farm and field scale. Regional differences are determined by climate and soil type while differences at farm scale have mainly socio-economic backgrounds (Tittonell et al., 2005). Zingore et al. (2007) recorded positive nutrient balances on wealthier farms due to high manure and mineral fertilizer input. Within a farm, the soil fertility is strongly affected by field utilization and distance of the field to the homestead, where closer plots are receiving more fertilizer (Vanlauwe et al., 2006 and Tittonell et al., 2005).

It is generally known that the incorporation of fertilizers is increasing yield and agricultural productivity. The combination of both, organic and mineral fertilizers is crucial as they influence different soil properties. Mineral fertilizers are characterized by a high concentration of plant available nutrients. Several studies showed a significant increase of grain yield after mineral fertilizer treatment (Pinitpaitoon et al., 2011). Drechsel et al. (2001) is claiming that fertilizer application is increasing with increasing population pressure at smallholder level. However the application rate is often insufficient due to the low availability and high cost of mineral fertilizers. Further, problems with acidification may occur after intensive addition of ammonium-based N fertilizers (Vanlauwe and Giller, 2006). On the other hand, organic amendments show a slower nutrient release pattern than mineral fertilizer but facilitate an increased soil organic matter (SOM) content (Pinitpaitoon et al., 2011). At smallholder level organic material is applied in form of farmyard manure (FYM) as it is often the only available source of organic matter (Dunjana et al., 2012). Although Vanlauwe and Giller (2006) claim that organic resources are not sufficient enough to supply crops with the required

nutrients, the increased SOM is enhancing productivity due to the improved biological activity and physical soil properties (Watson et al., 2002).

The importance of SOM to plant growth cannot be overemphasized and hence organic amendments play a significant role in agricultural production due to their positive effect on the physical soil properties, especially bulk density and aggregate stability.

Herencia et al. (2011) observed a high correlation between organic carbon (OC) content and some physical soil properties. Bulk density (BD) was decreasing with long-term application of organic fertilizers. The aggregate stability (AS) showed an increase with time on plots fertilized with organic matter. In general the increase in OC was significantly higher due to organic fertilizer than to mineral fertilizer application. Also Dunjana et al. (2012) recorded an increase of OC with increase of cattle manure application and further an increase of macro-AS. However, no significant effects on BD were recorded.

Improved AS facilitates water infiltration and hence increases the plant available water content and decreases runoff and erosion. Although there is little research on the interactions of SOM and infiltration, Franzluebbers (2002) recorded that greater SOM increased the infiltration rate by up to 27% on sandy loam soils in a humid subtropical climate.

It is widely researched that organic amendments contribute to higher OC values but the effects of mineral fertilizer on OC seem controversial. Hati et al (2007) realized a decline in OC due to 29 years of intensive cropping in all treatments, but the highest decline was at plots fertilized only by N-fertilizer. Soils fertilized by manure+NPK showed the highest OC value. Although mineral fertlilizers had no significant effect on OM, slightly increase of OM was recorded due to increased yield and biomass production (Celik et al., 2010). Rasool et al (2008) reported a higher increase of OC due to NPK application than to FYM application.

To study the divers soil fertility gradients in western Kenya, the Tropical Soil Biology and Fertility Institute of the International Centre for Tropical Agriculture (TSBF-CIAT) conducted an 8 year experiment on twelve Farms in the districts Vihiga and Siaya. Different treatment setups, including farmyard manure, Mavuno fertilizer and top dressing were applied to plots of high and low fertility. Two different maize varieties, the local variety and Imazapyr resistant maize, were planted twice a year during the short and long rainy season. The whole project had the aim to evaluate the effects of long-term fertilizer application on chemical, physical and biological soil properties, maize yield and further *Striga* spp. density in relation to the different soil fertility gradients in western Kenya.

2. Objectives and Hypotheses

2.1 Objective of the thesis

In the scope of this thesis physical soil properties of the topsoil such as bulk density, soil texture, infiltration rate and aggregate stability were determined. These parameters were analyzed on both, plots with high and plots with low fertility, which showed the following treatments: no fertilizer application (control), farmyard manure application alone and combined application of farmyard manure, Mavuno fertilizer and top dressing. The overall objective of this thesis was to assess how long-term organic and mineral fertilizer application was affecting the physical properties of the soil and to investigate the influence of the physical soil properties on the maize yield. Hence the maize yield harvested during the short rainy seasons (SR) was analyzed and related to the above mentioned parameters. Crop Evapotranspiration (ETc) and Water use efficiency were analyzed to exclude water deficiency as a crucial factor for the maize growth. Additional the organic carbon content was determined to investigate possible effects on the physical soil properties, especially on the AS.

2.2 Hypotheses

The hypotheses of this thesis are as followed:

- Long-term mineral and organic fertilizer application has an effect on physical soil properties and organic carbon.

- Physical soil properties and organic carbon do affect the maize growth and yield.

- Water deficiency is not a determining factor for maize growth in the Western Province of Kenya.

3. Background information – Western Province of Kenya

The experimental sites, Siaya and Vihiga are located in the Western Province of Kenya (Figure 1). Western Kenya is crossed by the equator and surrounded by Lake Victoria, Uganda and the Eastern Rift Valley. According to the agro-climatic zones (Figure 2) the Western province has a high to very high potential for plant growth with a very low risk of failure on adapted maize crops. The climate is semi-humid to humid with an average rainfall of 1000-2700 mm per year and average potential evaporation of 1200-2100 mm per year. Due to the two rainy and hence cropping seasons, the region has a high agricultural potential.

Figure 1. Map of Kenya (Wikipedia, 2011), Western Province marked in red

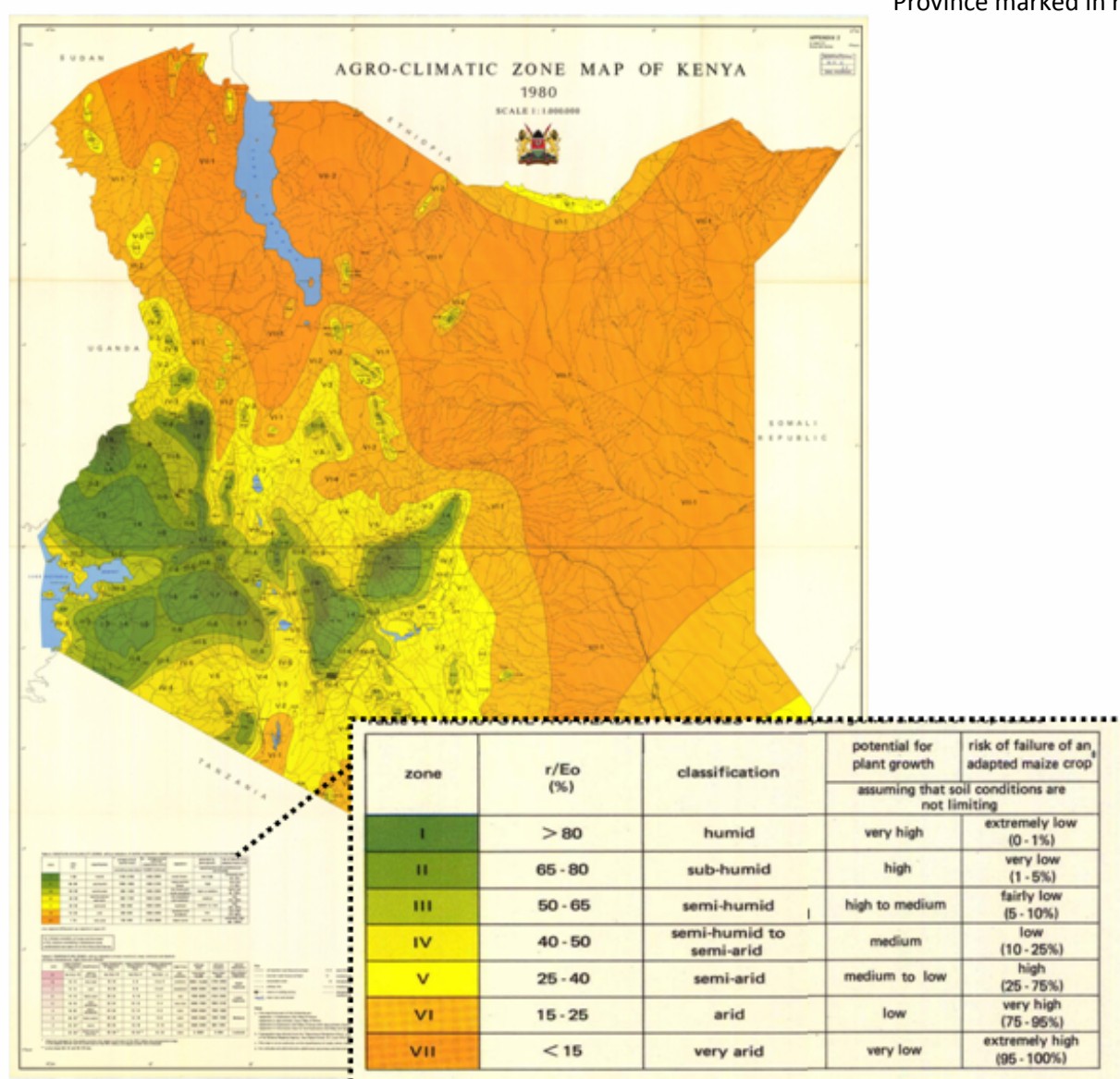| zone	r/Eo (%)	classification	potential for plant growth	risk of failure of an adapted maize crop assuming that soil conditions are not limiting
I	> 80	humid	very high	extremely low (0 - 1%)
II	65 - 80	sub-humid	high	very low (1 - 5%)
III	50 - 65	semi-humid	high to medium	fairly low (5 - 10%)
IV	40 - 50	semi-humid to semi-arid	medium	low (10 - 25%)
V	25 - 40	semi-arid	medium to low	high (25 - 75%)
VI	15 - 25	arid	low	very high (75 - 95%)
VII	< 15	very arid	very low	extremely high (95 - 100%)

Figure 2. Agro-Climatic zone Map of Kenya (Kenya Soil Survey, 1980)

Even though the Western Province is characterized by a high agricultural potential, the increasing population density, the soil types, low soil fertility and high poverty lead to low agricultural productivity. Further, nitrogen and phosphorus are the main limiting nutrients.

The rapid population growth is a main issue in whole Kenya. The population increased by a factor of 2.5 over 30 years and amount to over 38 million people in 2009 (CountrySTAT – Kenya, 2013). The population densities in 2001 in Vihiga and Siaya were 886 and 325 persons per km^2, respectively (GOK, 2005). The increase in rural population density and hence the increase in land-use intensity is causing low soil fertility. Further, due to the high population density the average farm size tends to be as small as 0.5 ha in Vihiga and 1.0 ha in Siaya (Jaetzold et al., 2005

The tropical soil can be divided into 3 groups based on their mineralogy. Almost 70% of the tropics are covert by unfertile low activity clay (LAC), soil as the red Ferralsols and Acrisols. The other two groups are the fertile, high activity clay (HAC) soils (Vertisols) and soils with amorphous or crypto-crystallized minerals as Andosols (Feller and Beare, 1997). The soil map (Figure 3) indicates a high diversity in soils in western Kenya. The diversity ranges from sandy and unfertile soils via sodic and strongly weather soils, through to deep red soils with high fertility.

Most of the farmers in western Kenya are aware of the low soil fertility and noticed an ongoing soil fertility depletion. Around 60% of surveyed farmers reported moderate to high soil fertility depletion rates. As cause of the depletion farmers stated soil erosion, inadequacy of manure supply, low technical know-how on soil fertility management practices and lack of cash for mineral fertilizers (Odendo et al., 2010).

Fertilizers are mainly applied in form of farmyard manure and crop residues. Nevertheless, a study on soil fertility management on smallholder farms in western Kenya (Tittonell et al., 2005) showed that many of the farmers are using fertilizers but the application rates are low and differ between farm types. Within that study, the farm types were classified by wealth; production orientation (self-consumption or market-oriented); constraints to land, labor and capital; family structure and main source of income. Mineral fertilizers are mainly applied as diammonium phosphate and calcium-ammonium nitrate and urea for top dressing. Small sized farms are less self-sufficient in food production and relay more on off-farm jobs, but dispose over a higher capital for mineral fertilizer purchase (Tittonell et al., 2005).

Besides decreasing soil fertility the parasitic weed *Striga* spp is a major problem for agricultural productivity in SSA (Sauerborn, 1991). Maize, which is the most important food crop in rural areas of Kenya (Shisanya et al., 2009) is greatly affected by this weed. Due to the land pressure and intensification of agricultural practices, the fallow periods tend to be shorter and the diversity of the crops lower. This and the decline in soil fertility create an ideal environment for *Striga* and other weeds. Further, farmers have little knowledge about *Striga* control (Oswald, 2005).
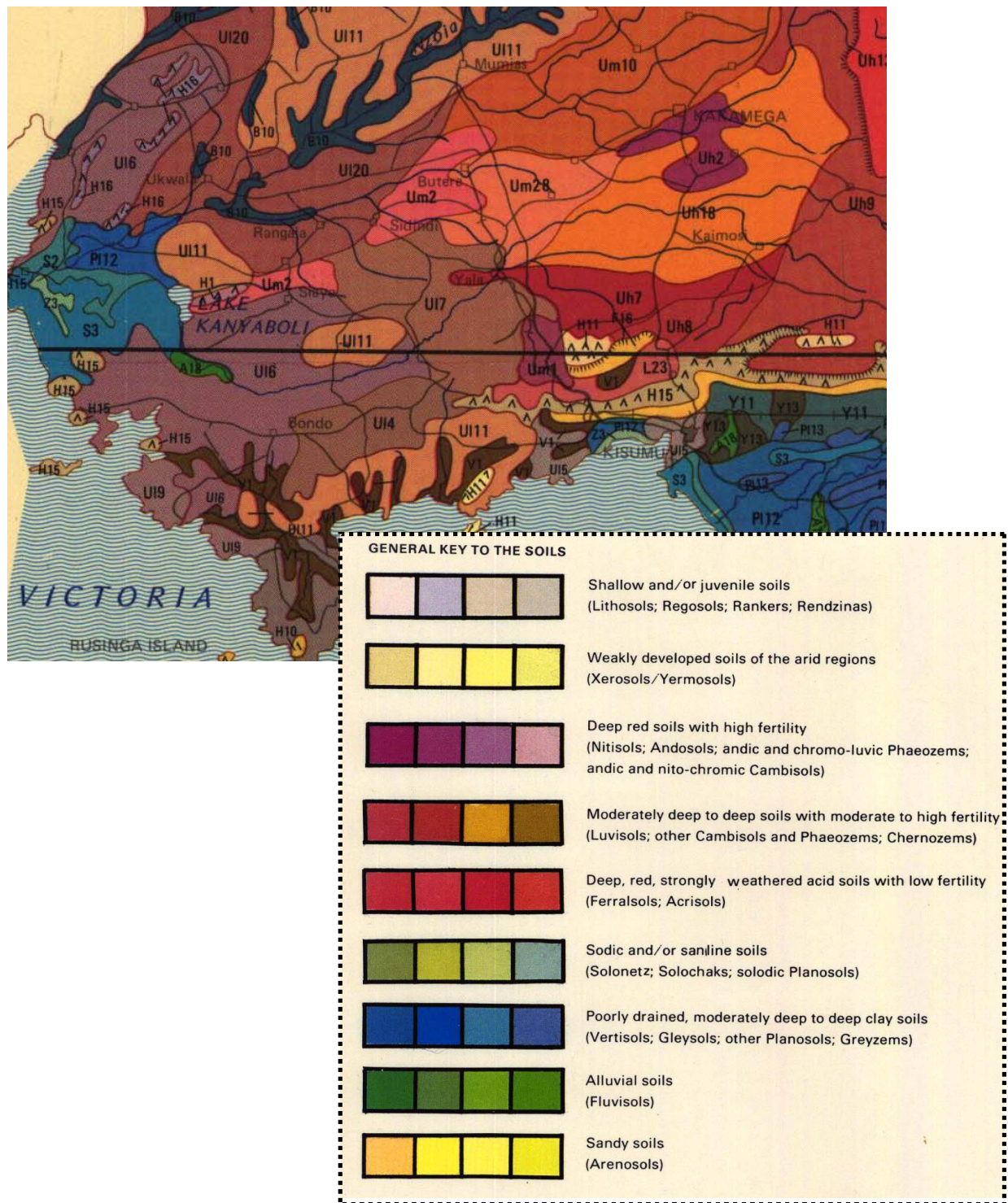
Figure 3. Soil Map of Kenya (Kenya Soil Survey, 1980), cut-out: Western Province

4. Materials and Methods

4.1 Site description

The study was conducted on three locations in the Western Province of Kenya: one location in the district of Vihiga and two locations, Nyalgunga and Nyabeda, in the district of Siaya (Figure 4). In each location four farms were selected. Table 1 is showing the precise location and elevation of the selected farms.
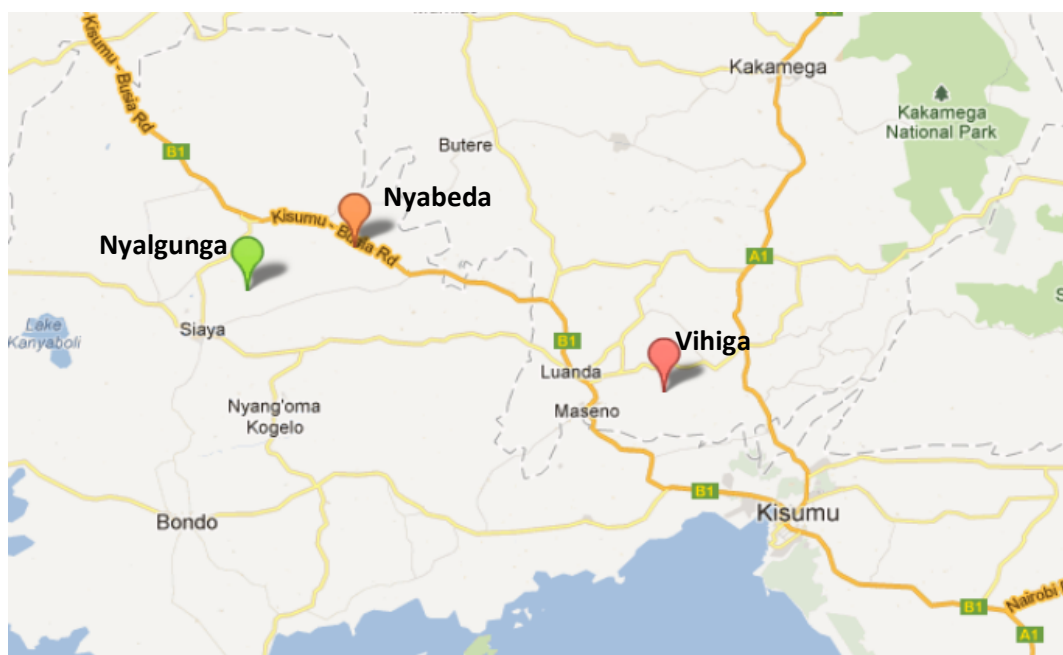
Figure 4. Location of the three study sites: Nyalgunga, Nyabeda, Vihiga (Google, 2012)

Table 1. Locations of the experimental Farms

District	Location	Farm Code	Northing	Easting	Elevation [m]
Siaya	Nyalgunga	SI/Y1/B1	0 04 50.1	34 18 21.8	1300
		SI/Y1/B2	0 04 42.6	34 18 19.1	1335
		SI/Y1/C1	0 04 56.9	34 13 17 .5	1312
		SI/Y1/C3	0 05 05.4	34 17 53 .3	1310
	Nyabeda	SI/Y2/A1	0 08 01.2	34 24 17.5	1347
		SI/Y2/A2	0 08 02.8	34 24 29.5	1360
		SI/Y2/B2	0 07 42.9	34 24 29.5	1323
		SI/Y2/C2	0 07 50.5	34 24 10 .8	1333
Vihiga	Emusutswi	VI/Y2/0	0 07 39.1	34 40 17.2	1528
		VI/Y2/A3	0 07 36.2	34 40 46.2	1510
		VI/Y2/B1	0 07 23.2	34 40 26.0	1503
		VI/Y2/C1	0 07 30.0	34 40 11.9	1470

The climate in the Western Province is characterized by two rainy seasons: the long rainy season (LR) from March to July and the short rainy season (SR) from August to December. On each farm the rainfall was recorded on daily basis. Appendix 1 is showing the total annual rainfall amount between 1998 and 2011 for each farm. The average annual rainfall for this period in Nyalgunga, Nyabeda and Vihiga is 1848 mm, 1895 mm and 1911 mm, respectively.

Additional metrological data was taken from the FAO WATER (2012) database ClimWat. According to the Agro-ecological zoning (AEZ), data from the metrological station in Kakamega (Table 2) is representative for the Location Vihiga and data from the metrological station in Tororo/Uganda (Table 3) can be used within the district Siaya.

Table 2. Average (1971 - 2000) metrological data from Kakamega (FAO WATER, 2012)

Month	Temperature max [°C]	Temperature min [°C]	Humidity [%]	Wind speed [m/s]	Sunshine [h]	Radiation [MJ/m2/d]	Eto [mm/d]
January	31.1	10.3	60.4	1.0	8.00	21.13	3.96
February	32.0	10.7	58.9	1.0	8.00	21.85	4.15
March	32.6	10.8	62.3	1.2	7.60	21.45	4.17
April	31.4	10.5	73.1	0.9	6.50	19.14	3.61
May	30.9	10.3	75.1	0.8	6.80	18.57	3.35
June	29.7	9.9	74.0	0.8	7.30	18.62	3.26
July	30.3	10.1	73.4	0.8	6.90	18.29	3.20
August	29.4	9.8	72.5	0.9	7.30	19.77	3.49
September	30.0	10.0	70.1	0.9	7.10	20.28	3.66
October	30.8	10.3	68.3	1.0	7.20	20.54	3.82
November	30.8	10.3	67.9	1.1	6.50	18.96	3.63
December	30.7	10.2	65.2	1.3	7.90	20.64	3.88

Table 3. Average (1971 - 2000) metrological data from Tororo, Uganda (FAO Water, 2012)

Month	Temperature max [°C]	Temperature min [°C]	Humidity [%]	Wind speed [m/s]	Sunshine [h]	Radiation [MJ/m2/d]	Eto [mm/d]
January	30.6	15.8	58.1	2.2	6.69	19.08	4.50
February	30.7	16.5	58.5	2.2	7.46	20.96	4.83
March	30.1	17.0	63.2	2.2	6.55	19.79	4.57
April	28.5	17.0	73.0	1.8	7.67	20.96	4.21
May	27.5	16.8	76.2	1.6	6.77	18.58	3.66
June	27.2	16.2	74.2	1.8	7.25	18.62	3.64
July	26.8	16.0	73.2	1.8	6.53	17.82	3.55
August	27.1	15.7	72.7	1.8	5.49	17.11	3.52
September	28.1	15.7	71.0	1.8	6.19	18.87	3.88
October	29.0	16.0	69.3	1.8	7.00	20.21	4.16
November	29.0	16.1	67.6	2.0	7.91	21.05	4.33
December	29.2	16.0	64.2	2.0	7.46	19.92	4.25

The main soil types in Vihiga are Haplic Acrisols and in Siaya Rhodic Nitisols.

Nitisols are red soils with at least 30 % clay and fair water holding properties. These soils are among the most productive soils of the humid tropics due to the high cation exchange capacity and available soil water (Jaetzold et al., 2005). Due to high P sorption application of slow-release P fertilizers is required. The rhodic type has a subsurface layer within 150 cm of the soil surface with a Munsell hue redder than YR (FAO, 2006b).

Acrisols are characterised by acidic pH, a higher clay content in the subsoil than in the topsoil and by low-activity clays in certain depths. The application of fertilizers on these soils is necessary to achieve rewarding and productive farming. Further, FAO (2006b) recommends the growing of undemanding and acidity-tolerant crops on Acrisols.

4.2 Plot design and treatment structure

With the implementation of the Soil Fertility Gradients project by CIAT-TSBF in 2004, trails with high and low fertility were defined on each of the twelve farms. The criteria for selecting high and low fertility fields within one farm were based on:
- farmers perception, considering local soil quality indicators such as soil colour and weed type,
- the farmers crop yield history,
- proximity to the homestead,
- soil carbon levels, which were determined by spectral analysis and
- visual degradation features such as erosion, *Striga* spp weed and surface crusting.

Those trails were split in plots with different treatments (Table 4) which were arranged as a randomized complete block design. The size of one plot was 25,2 m² (6 x 4.2 m). Organic and mineral fertilizers were applied at the same time as the sowing of the maize took place. Farmyard manure was applied at the rate of 15 kg per plot and Mavuno fertilizer (N:P:K – 10:26:0) at the rate of 149 kg/ha. The Mavuno fertilizer contains 10% N, 26% P_2O_5, 14% CaO, 4% MgO, 4% S and trace elements such as Bo, Mn, Zn, Na and Cu. Mavuno top dressing was applied six weeks after planting to one half of the plots at the rate of 99kg/ha. Hence the representative plot size for TD plots was 12.6 m².

Table 4. Treatment structure of the Soil Fertility Gradients project by TSBF-CIAT

No.	Treatment description
T1	LM (no fertilizer added)
T2	IR (no fertilizer added)
T3	IR + MAV
T3 TD	IR + MAV + TD
T4	IR + MAN
T4 TD	IR + MAN + TD
T5	IR + MAV + MAN
T5 TD	IR + MAV + MAN + TD

T= Treatment, LM = local maize, IR = Imazapyr resistant maize, MAV = Mavuno Fertilizer, MAN = Farmyard manure, TD = Top dressing. The highlighted treatments were analyzed in scope of this thesis.

In scope of this thesis samples from treatment T2, T4 and T5 TD were analyzed. On the control plot (T2) no additional fertilizers were applied. Treatment T5 TD was representing the best case scenario with FYM, Mavuno fertilizer and top dressing. Treatment T4 was fertilized only by FYM. Within this thesis treatment T5 TD is called T5.

4.3 Maize yield

The maize was planted and harvested continuously twice a year, during the short and long rainy seasons. The maize was planted with a spacing of 30 cm by 75 cm in each plot. Ten days after sowing the germinated maize seeds were collected and non-germinated gaps were filled with new seeds. Local maize was sowed on plot T1 with no other addition of fertilizers. On all the other plots Imazapyr resistant maize was planted, that is coated with herbicide to make it resistant to *Striga* spp weed.

The yield data analyzed within this thesis is the maize harvested after the short rain season in 2011. Table 5 is showing the planting and harvesting dates of the three locations. To avoid errors, maize growing at the boundaries of the plots was not taken into account. Therefore the effective harvest area was 16,8 m^2 for treatment T2 and T4 and 7,08 m^2 for treatment T5. The measured components of the maize plant were: stalk, ear, grain, shelled grain and stovers weight. The yield was calculated as followed:

maize yield = (ear whole fresh weight * grain sample dry weight) / grain sample fresh weight / harvested area [kg/plot]

4.4 Crop Evapotranspiration and Water use efficiency

The crop evapotranspiration (ETc) was determined by the crop coefficient curve approach according to the FAO (1998) guidelines for single crop coefficient (Kc). The FAO is assuming a growing period of 180 days for East Africa. As the climate in western Kenya is relatively humid the growing period in the three locations is between 121 and 125 days (Table 5). Therefore it seemed more suitable to calculate with the length of growth stages from humid Nigeria, which is showing the following lengths for initial, development, mid and late stage respectively: 20, 35, 40 and 30 days.

Table 5. Planting and harvesting dates of the tree locations

Location	Date planted	Date harvested	Total days	Total rainfall [mm]	Daily rainfall [mm]
Vihiga	14th September 2011	16th January 2012	125	732	5.9
Nyabeda	12th September 2011	10th January 2012	121	761	6.3
Nyalgunga	13th September 2011	13th January 2012	123	722	5.9

To construct the crop coefficient curve the Kc values for the initial stage (Kc ini), the mid-season stage (Kc mid) and for the late season stage (Kc end) are required. For maize grown in a subhumid climate with a relative humidity of 45% and wind speed of 2 m/s, those values are 0.3, 1.2 and 0.6-0.35, respectively. Kc end depends on the grain moisture at harvest. Where the second value (0.35) for harvest of dry grain of about 18% moisture at wet mass basis. The overall average grain moisture for this project is 33.7 %. Therefore the assumed Kc end is 0.6.

The Kc ini was adjusted according to figure 29 in Chapter 6 - ET_c - Single crop coefficient (FAO, 1998). This figure is mainly used for light to medium wetting events and when wetting is only by precipitation. To use the figure the average rain interval was calculated from the rain data from the short rains 2011.

Kc mid and Kc end were adjusted to the climatic condition in western Kenya by the following equation:

$$Kc = Kc(table) + [0.04*(u-2) - 0.004 (RH - 45)] * (h/3) 0.3$$

> where:
> Kc(table) = the value for Kc mid or Kc end according to the FAO
> u = the mean daily wind speed in m/s
> RH = the mean daily relative humidity in %
> h = the mean maximum plant height in m

The data used for the adjustment of the Kc mid and Kc end was averaged according to the growing period during the short rains 2011 in each location (Table 6).

Table 6. Average values for reference evapotranspiration (ETo), relative humidity (RH) and wind speed (u) according to crop stage and location

	Crop stage	Location		
		Nyalgunga	Nyabeda	Vihiga
ETo [mm/d]	ini	3.91	3.89	3.68
	dev	4.19	4.18	3.78
	mid	4.30	4.30	3.74
	end	4.37	4.35	3.92
RH [%]	ini	70.8	70.9	69.8
	dev	69.0	69.1	68.2
	mid	66.2	66.3	66.8
	end	61.4	61.9	62.6
u [m/s]	ini	1.80	1.80	0.92
	dev	1.83	1.83	1.02
	mid	2.00	2.00	1.19
	end	2.09	2.08	1.14

The Kc during the crop development and late season stage varies linearly between the Kc values of the previous and next stage and was adjusted according to the following equation:

$$K_{c\,i} = K_{c\,prev} + [(i - \sum L_{prev}) / L_{stage}] * (K_{c\,next} - K_{c\,prev})$$

where:
i = day number within the growing season
$K_{c\,i}$ = crop coefficient on day i
L_{stage} = length of the stage under consideration [d]
$\sum L_{prev}$ = sum of the lengths of all previous stages

To estimate irregularities in rainfall patterns over the study period of 8 years it was summed that the SR occurred always between the 12th of September and the 16th of January.

4.5 Infiltration rate measurement

The infiltration rate (IF) was measured on the control treatment (T2) and on treatment T5. As some of the farmers had already ploughed their fields and hence disturbed the top soil, the IF could only be measured on the following farms: VI/Y2/B1, SI/Y1/B2, SI/Y1/C3, SI/Y1/C1, SI/Y2/B2, SI/Y2/C2 and SI/Y2/A1. The measurement was conducted once per treatment, at the same time as the soil sampling was done before the planting in February 2012. At the time the measurements were taken, the soil was very dry and bare. The measurement set-up was as followed:

A steeled infiltration ring with 30 cm diameter was driven about 2 to 3 cm into the soil. The soil was pre-wetted with 5 l of water for 20 min. Then the ring was filled up with water till the level of 20 cm. For the first 20-30 min the data was recorded at 5 min intervals. Later the readings were taken every 15 min, till the infiltration rate has stabilized. After each reading the water level was usually toped up to 20 cm. It was assumed that the IF stabilized when the readings showed 3 times the same values.

The IF was then calculation according to the following formula:

IF = (Start level – End level) / Interval [cm/min]

4.6 Soil Sampling

For the laboratory analysis of soil texture, aggregate stability and organic carbon, soil samples were collected at the same time as the IF was measured in February 2012. Per each treatment 6 sub-samples were taken with an auger from the topsoil (0-15 cm) according to the W-method. Then the collected soil was gently mixed to obtain a representative sample. Approximately 1.5 kg of this sample was stored in a sampling bottle to protect the aggregates during transport.

Simultaneously, bulk density (BD) was determined on undisturbed soil using cores with 5 cm height and diameter. Due to ploughing, the BD could be only determined at the same farms as IF. Sampling was repeated randomly, 3 times in each treatment.

4.7 Laboratory analysis

4.6.1 Soil texture and texture classes

Soil texture was determined at the lab of CIAT-TSBF in Nairobi by the hydrometer method (Appendix 4). The texture classes were defined according to the textural triangle by FAO (2006a).

4.6.2 Bulk density

Core samples were dried over 24 hours at 105°C and calculated according to the following formula:

BD = Dry weight / Core Volume [g/cm3]

where the core diameter and height were 5 cm.

4.6.3 Aggregate stability

The Aggregate stability (AS) was analyzed at the University of Nairobi, Department for Land Resources Management and Agricultural Technology according to Yoder (1936). Approximately 100 g of air dried sample was sieved between 2 and 4 mm. The sample was pre wetted over 5 min and then wet sieved over 10 min due to a mechanical shaker. Six sieves were used with the sizes: 2.0, 1.0, 0.5, 0.25, 0.125 and 0.063 mm. The retained aggregates of each sieve were oven dried at 105°C and weighted. To correct the designation of sand particles as false aggregates, the material from each sieve was dispersed and stirred over 7 min. The dispersion solution was made out of 33 g Sodium hexametaphosphate and 7 g sodium carbonate in 1 litre distilled water. After dispersion the sample was sieved again and dried to determinate the new weight. The aggregate stability for each size was calculated as following:

AS = (weight retained – weight of sand) / (total sample weight – weight of sand) x100

The total aggregate stability was defined as the sum of the AS values for each size.

4.6.4 Organic carbon

The Organic carbon (OC) was determined at the University of Nairobi, Department for Land Resources Management and Agricultural Technology according to the Walkley-Black procedure (Walkley, 1946).

4.8 Statistical analysis

The statistical set-up of the study and the split plot design are shown in Figure 5. In each of the three locations the four farms acted as repetitions. Each farm was split into high and low fertility plots, which further were split into the treatments (T2, T4, T5).
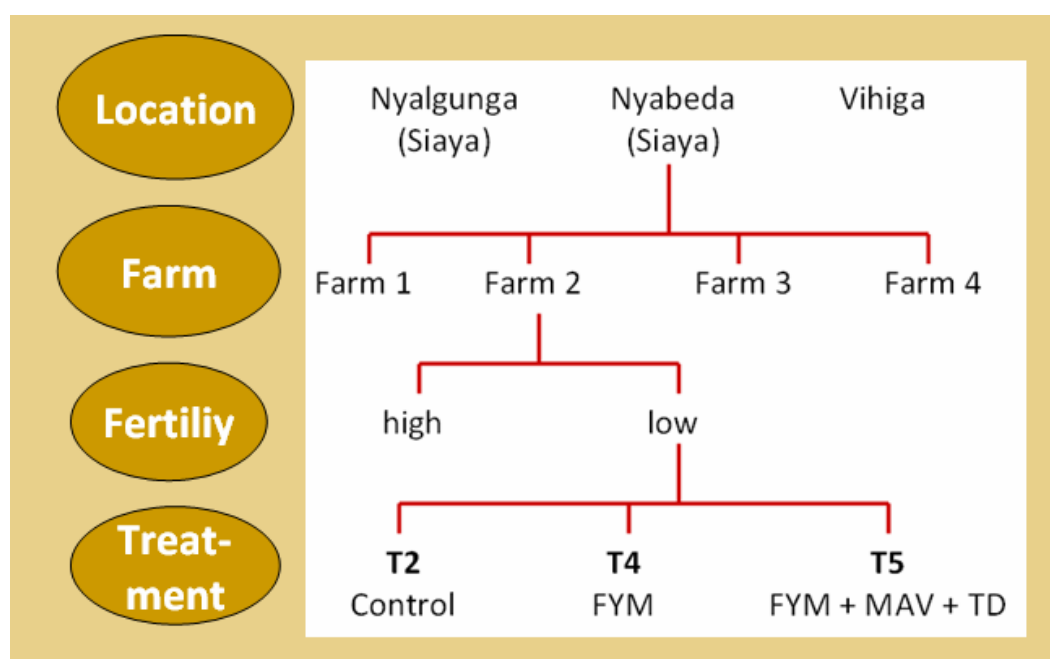
Figure 5. Split plot design of the study.
T: Treatment, FYM: Farmyard manure 15 kg per plot, MAV: Mavuno fertilizer (N:P:K –
10:26:0) 149kg/ha, TD: Mavuno top dressing 99kg/ha (applied 6 weeks after planting)

The comparison between the physical soil properties at different locations, fertilities and treatments was done by applying single factor analyses of variance (ANOVA). First the parameters were analyzed within one location and fertility, later the differences between the locations were determined. Simple correlations between the soil properties were carried out to explain their relation to each other. All data analyses were conducted with MiniTab and MS Excel.

5. Results

5.1 Crop Evapotranspiration and Water use efficiency

The total rainfall amount during the cropping SR 2011 in Nyalgunga, Nyabeda and Vihiga was 730 mm, 764 mm and 740 mm, respectively. Approximately 45% of the total rainfall occurred during the development stage of the crop, 32-38 % during the mid stage and only 2% during the late stage (Figure 6). The rain events were uneven spread during the cropping season and varied in magnitude between < 1mm and 81.3 mm. In average the rainfall intervals were 1.6 days in Nyalgunga and 1.8 days in Nyabeda and Vihiga. Table 7 summarizes some characteristics of the rain events. Daily rainfall data is illustrated in Appendix 3.

Table 7. Characteristic of the rain events during the short rains season 2011

	Location		
	Nyalgunga	Nyabeda	Vihiga
Total rain amount [mm]	730	764	740
Count of rain events	80	71	72
Count of rain events higher than 10 mm	26	35	24
Count of rain events higher than 20 mm	10	11	10
Average rainfall per event [mm/d]	9.1	10.7	10.3
Maximal rainfall [mm/d]	56.9	69.3	81.3
Average rainfall interval [d]	1.6	1.8	1.8
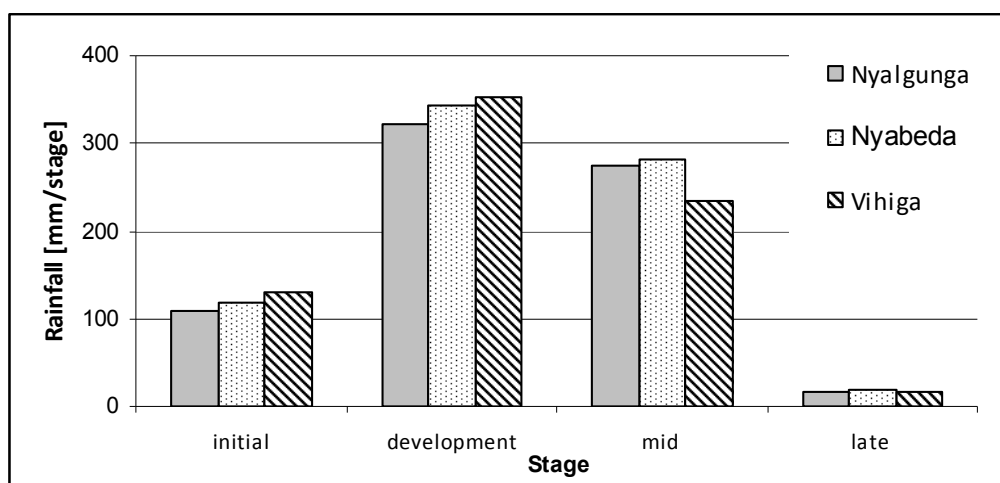
Figure 6. Total rainfall for each growing stage and location

The results of the Kc are demonstrated in Table 8. In Nyabeda and Nyalgunga the results were quite similar as those are based on the same metrological data. These values are the basis for the calculation of the ETc and the water balance.

Table 8. Kc values according to crop stage and location

Crop stage	Location		
	Nyalgunga	Nyabeda	Vihiga
initial	0.63	0.60	1.08
mid	1.12	1.12	1.09
end	0.55	0.54	0.51

In Nyalgunga and Nyabeda the daily average ETc ranged from 2.34 to 4.84 mm/day and decreased in the following order: mid stage> development > late stage > initial. In Vihiga the range of ETc was narrower: from 3.01 to 4.11 mm/day. Main difference between Siaya and Vihiga was the higher ETc during initial crop stage in Vihiga. The water balance was in all stages positive, except the late stage where the water deficit was between 2.42 and 2.77 mm/d. Highest water surpluses were recorded in the development stage of the crop (Table 9). Appendix 3 contains the results of ETc and the water balance on daily basis.

Table 9. Average Rainfall, Etc and Water balance per crop stage during SR 2011

Location	Crop Stage	Rainfall [mm/stage]	ETc [mm/stage]	Water Balance [mm/stage]	Rainfall [mm/d]	ETc [mm/d]	Water Balance [mm/d]
Nyalgunga	initial	108.67	49.24	59.43	5.43	2.46	2.97
	development	320.96	129.89	191.07	9.17	3.71	5.46
	mid stage	274.61	193.37	81.24	6.87	4.83	2.03
	late stage	17.34	100.31	-82.97	0.58	3.34	-2.77
Nyabeda	initial	118.04	46.73	71.31	5.90	2.34	3.57
	development	343.96	127.56	216.40	9.83	3.64	6.18
	mid stage	280.88	193.41	87.47	7.02	4.84	2.19
	late stage	18.18	92.51	-74.33	0.61	3.08	-2.48
Vihiga	initial	129.16	79.57	49.59	6.46	3.98	2.48
	development	351.99	143.92	208.07	10.06	4.11	5.94
	mid stage	233.58	163.54	70.04	5.84	4.09	1.75
	late stage	17.68	90.33	-72.65	0.59	3.01	-2.42

Within two preceding months before the SR 2011 total rainfall amounts Nyalgunga, Nyabeda and Vihiga were 428 mm, 455 mm and 462 mm, respectively. Table 10 compares rainfall data from previous years during the SR.

Table 10. Total rainfall during SR (12. September - 16. January)

Year	Nyalgunga	Nyabeda	Vihiga
1998	506	519	484
1999	659	661	625
2000	720	740	721
2001	664	677	723
2002	747	759	715
2003	481	483	492
2004	620	618	616
2005	391	398	398
2006	1128	1160	1088
2007	475	488	490
2008	653	674	655
2009	729	737	818
2010	500	519	579
2011	731	764	740
Mean	**643**	**657**	**653**

5.2 Maize yield

The overall maize yield, including all the three treatments as well as the high and low fertility plots, showed significant differences ($p<0.005$) between the three locations. Figure 7 is showing a boxplot with the minimum and maximum yield values for each farm. The individual data is illustrated in Appendix 2. The yield is decreasing from Nyalgunga, over Nyabeda till Vihiga with yield means of 2721, 1802 and 970 kg/ha, respectively. The farm SI/Y1/C3 within location Nyalgunga is an outlier. The harvest was destroyed by animals and therefore these data is not representative for this location. In general, there are no significant differences between the farms within one location.
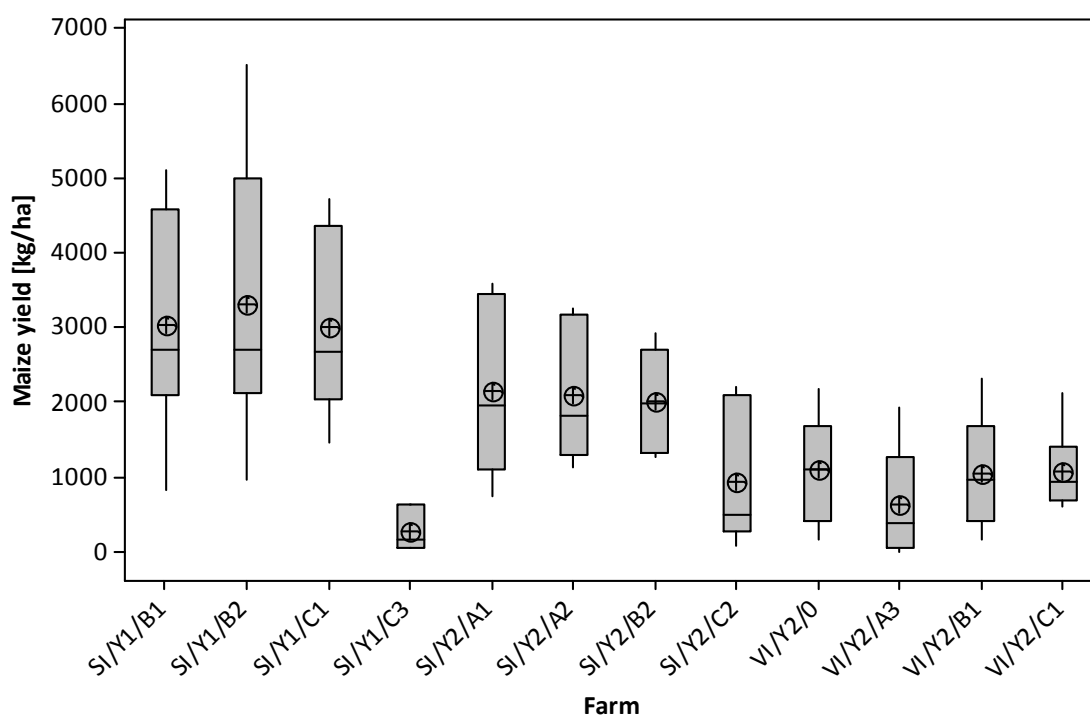
Figure 7. Boxplot of maize yield in kg/ha for each farm

The maize yield increased with the treatment, where T5 shows the highest yield and T2 the lowest. This trend is statistically significant and evident in all locations (Table 11). None of the locations show significant differences between high and low fertility. Nevertheless, the average maize yield for each treatment is slightly higher at the low fertility plots than at the high fertility plots.

Table 11. Mean maize yield in kg/ha and p-value

Location	T2	T4	T5	p
Vihiga	349	973	1586	0.000
Nyabeda	1043	1697	2665	0.002
Nyalgunga	1562	2882	3719	0.052
Mean	960	1806	2611	0.000

5.3 Soil texture

Table 12 shows the particle size distribution in the topsoil for each farm and fertility level. The data indicates significantly lower clay (p=0.000) content in Vihiga than in Siaya. In Siaya the mean clay contend was 40% and the texture class is dominated by a sandy clay. Where in Vihiga the clay content had a mean value of 31% and the texture class was sandy clay loam.

Table 12. Soil texture analysis for each farm and fertility level and definition of texture classes according to FAO (2006)

Location	Farm	Fertility	Soil texture [%]			Texture classes
			Clay	Sand	Silt	
Nyalagunga	SI/Y1/B1	H	40.9	47.1	12.0	sandy clay
	SI/Y1/B1	L	51.2	37.0	11.8	clay
	SI/Y1/B2	H	29.6	60.4	10.0	sandy clay loam
	SI/Y1/B2	L	38.3	49.7	12.0	sandy clay
	SI/Y1/C1	H	47.2	39.6	13.2	clay
	SI/Y1/C1	L	41.6	48.4	10.0	sandy clay
	SI/Y1/C3	H	32.9	53.7	13.3	sandy clay loam
	SI/Y1/C3	L	38.9	50.4	10.7	sandy clay
Nyabeda	SI/Y2/A1	H	41.6	46.4	12.0	sandy clay
	SI/Y2/A1	L	42.2	46.4	11.3	sandy clay
	SI/Y2/A2	H	40.3	47.1	12.7	sandy clay
	SI/Y2/A2	L	40.3	46.4	13.3	sandy clay
	SI/Y2/B2	H	31.6	56.4	12.0	sandy clay loam
	SI/Y2/B2	L	45.2	39.6	15.2	clay
	SI/Y2/C2	H	40.2	47.1	12.7	sandy clay
	SI/Y2/C2	L	40.2	47.8	12.0	sandy clay
Vihiga	VI/Y2/0	H	29.3	62.2	8.5	sandy clay loam
	VI/Y2/0	L	30.3	58.4	11.3	sandy clay loam
	VI/Y2/A3	H	31.6	56.4	12.0	sandy clay loam
	VI/Y2/A3	L	32.9	56.4	10.7	sandy clay loam
	VI/Y2/B1	H	30.3	60.4	9.3	sandy clay loam
	VI/Y2/B1	L	27.6	62.4	10.0	sandy clay loam
	VI/Y2/C1	H	32.9	55.1	12.0	sandy clay loam
	VI/Y2/C1	L	32.3	57.8	10.0	sandy clay loam

5.4 Infiltration rate

The infiltration rate varies between 0.09 and 0.63 cm/min with an overall average of 0.39 cm/min. The average values for Nyabeda, Nyalgunga and Vihiga are 0.41, 0.37 and 0.31 cm/min, respectively. Table 13 shows the IF for each plot. Differences in IF between the farms are significant (p=0.000). There are no significant differences, neither in treatment nor in fertility levels. The regression with BD and OC does not show any clear patterns.

Table 13. Infiltration rate in cm/min for each farm, fertility and treatment

Location	Farm	Fertility	Treatment	Infiltration rate
Nyalgunga	SI/Y1/B2	H	T2	0.27
	SI/Y1/B2	H	T5	0.47
	SI/Y1/B2	L	T2	0.47
	SI/Y1/B2	L	T5	0.40
	SI/Y1/C1	H	T2	0.57
	SI/Y1/C1	H	T5	0.55
	SI/Y1/C1	L	T2	0.61
	SI/Y1/C1	L	T5	0.48
	SI/Y1/C3	H	T2	0.09
	SI/Y1/C3	H	T5	0.27
	SI/Y1/C3	L	T2	0.23
	SI/Y1/C3	L	T5	0.23
Nyabeda	SI/Y2/A1	H	T2	0.63
	SI/Y2/A1	H	T5	0.60
	SI/Y2/A1	L	T2	0.57
	SI/Y2/A1	L	T5	0.34
	SI/Y2/B2	H	T2	0.42
	SI/Y2/B2	H	T5	0.53
	SI/Y2/B2	L	T2	0.50
	SI/Y2/B2	L	T5	0.33
	SI/Y2/C2	H	T2	0.27
	SI/Y2/C2	H	T5	0.28
	SI/Y2/C2	L	T2	0.21
	SI/Y2/C2	L	T5	0.23
Vihiga	VI/Y2/B1	H	T2	0.30
	VI/Y2/B1	H	T5	0.43
	VI/Y2/B1	L	T2	0.33
	VI/Y2/B1	L	T5	0.29

5.5 Bulk density

Table 14 shows the mean values for BD for each farm with an overall mean value of 1.16 g/cm³. The average BD on sandy clay loam soils is 1.20 g/cm³, and on sandy clay soils 1.14 g/cm³. In Nyabeda the differences in BD between farms are statistically significant (p=0.022). There are no significant differences, neither between treatments, nor between high and low fertility.

Table 14. Bulk density in g/cm³ for each farm and fertility

Location	Farm	Fertility	Bulk density
Nyalgunga	SI/Y1/B2	H	1.20
	SI/Y1/B2	L	1.10
	SI/Y1/C1	H	1.15
	SI/Y1/C1	L	1.17
	SI/Y1/C3	H	1.20
	SI/Y1/C3	L	1.19
Nyabeda	SI/Y2/A1	H	1.13
	SI/Y2/A1	L	1.10
	SI/Y2/B2	H	1.17
	SI/Y2/B2	L	1.19
	SI/Y2/C2	H	1.08
	SI/Y2/C2	L	1.09
Vihiga	VI/Y2/B1	H	1.19
	VI/Y2/B1	L	1.22

5.6 Organic carbon content in soil

The mean OC level by weight in Nyabeda, Nyalgunga and Vihiga is 1.85, 1.35 and 1.52%, respectively. The differences between the locations are statistically significant (p=0.001). There are no significant differences between the high and low fertility. The overall means for treatment T2, T4 and T5 are 1.32, 1.32 and 2.07%, respectively. The OC content among treatment T5 is significantly higher (p<0.005) than treatment T2 and T4 (Figure 8). The results do not show differences between treatment T2 and T4. The individual data is illustrated in Appendix 2.
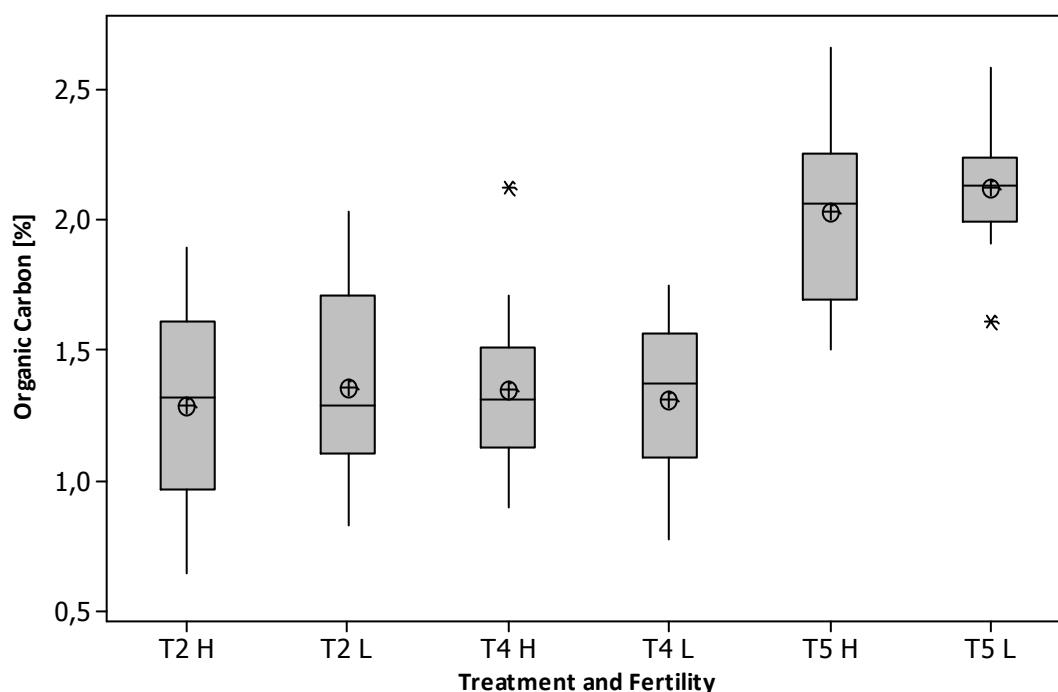
Figure 8. Boxplot of the OC content in the soil at each treatment and fertility level in % by weight

5.7 Aggregate stability

The individual results of the AS in relation to location, farm, fertility level and treatment are illustrated in Appendix 2. Figure 9 shows the individual value plot of the results according to treatment and fertility level. The values vary between 79.2 and 15.5 % and indicate a high variability of the results.
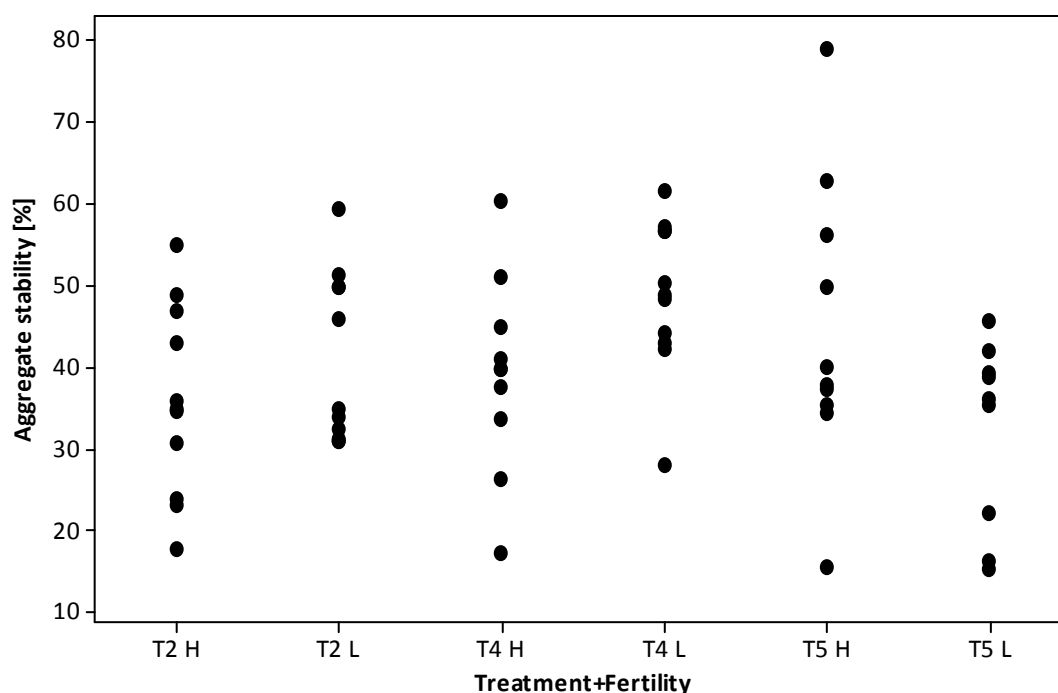
Figure 9. Individual value plot of the AS in % by weight

The AS in Nyabeda, with a mean value of 48%, is significantly higher (p=0.011) than in Nyalgunga and Vihiga, where the AS is 37% and 38%, respectively. In Nyabeda and Vihiga the mean AS seems to be higher on treatment T4 (Table 15), but this tendency is statistically not significant. The data does not indicate differences in AS between plots with high and low fertility at any of the locations.

Table 15. Mean Aggregate stability and Standard Deviation in % by weight

Location	T2		T4		T5		p-value
	Mean	StDev	Mean	StDev	Mean	StDev	
Vihiga	32.5	8.8	43.8	5.6	37.4	13.6	0.082
Nyabeda	45.9	9.6	52.6	9.1	44.7	10.1	0.325
Nyalgunga	39.0	11.9	35.5	14.4	35.5	21.9	0.894

6. Discussion

6.1 Crop Evapotranspiration and Water use efficiency

The rainfall events in western Kenya were not equally spread, neither during the cropping season nor during the particular crop stage. Additionally, the rainfall events occurred in various high intensities and the exact duration of an event is unknown. Extreme rain events that often occur in the tropics can damage the crop and further result in high runoff when the infiltration capacity of the soil is exceeded. The highest rain amount precipitated at all sites during the development and mid stage, where the ETc was also highest. The lowest precipitation amounts were found during the late stage, where only during 6% of the stage length in Nyabeda and 3% in Vihiga and Nyalgunga, rain events occur.

The ETc, varied between 2.34 and 4.84 mm/day and was highest during the development and late stage of the growing season. The results of the ETc are comparable with other studies about water requirements of maize. Kang et al. (2003) investigated ETc within the range of 1.56 – 5.33 mm/day. That study was conducted between June and October on a loess loam soil in the semi-humid climate of Province Shaanxi in China. A study by Gao et al. (2009) in Henan Province of China showed that ETc does vary between the crop stages. The ETc rose from approximately 1.5 mm/day in the initial stage up to almost 6 mm/day during mid stage and declined in the end below 1 mm/day.

Taking into account the whole cropping period, the rainfall amount is able to cover the water requirements of maize at all sites, during all crop stages except the late stage. The negative water balance during late stage might even have a positive effect on the maize storage due to lower grain moisture at harvest.

Nevertheless, a major flaw of this study is the missing information about the water holding capacity of the soil. The texture results did show significant differences in clay content between Siaya and Vihiga. Hence it is unclear in what proportion the infiltrated rainwater is available for the plants.

Further, daily rainfall data was collected at the sites, the calculation of the Crop Evapotranspiration (ETc) for the growing season short rains 2011 was based on monthly average data from metrological stations in the same Agro-economic zones at the sites. Hence the final results of the ETc can only be seen as a rough estimation to predict water requirements for the maize grown in Siaya and Vihiga.

6.2 Soil fertility gradients

A main objective of the conducted study was to investigate differences between soil fertility gradients that are claimed to occur within farms. Neither the maize yield, nor any of the physical soil parameters indicate significant differences between the high and low fertility plots. The maize yield shows slightly higher values in the low fertility plots, although it was expected to be higher in the high fertility plots. The data indicates that there are no differences in soil fertility gradients within farms for all three locations.

However, several studies (Vanlauwe et al., 2006 and Tittonell et al., 2005) proved that soil fertility in western Kenya is affected by the field utilization and proximity to the homestead. Two possible hypotheses are coming up to explain that lack of clarity. Fist, the criteria for selecting high and low fertility plots, might have been too subjective and not based enough on scientific data to emphasize the differences. Furthermore, the differences between high and low fertility are more descriptive and do not indicate the level of fertility. Second, as mentioned in the introduction, the high fertility plots are resulting from more intensive fertilizer input close to the homestead. In scope of this study, the trials were fertilized every cropping season in the same way and that over eight years. It might well be that the fertility gradients within one farm were balanced out since the implementation of the trials.

6.3 Maize yield

It seems that the differences in maize yield between the treatments are due to the different nutrient levels. As hypothesized the maize yield is lowest at the control plot (T2) with no additional fertilizer input. The maize yield on treatment T4, which was fertilizer with FYM, is higher than treatment T2. Finally, treatment T5, which is assumed to be the best case scenario with FYM, Mavuno fertilizer and top dressing, shows the highest yield. These patterns are clearly evident in all three locations. Several studies (Gentile et al., 2008; Donovan and Casey, 1998 and Shisanya et al. 2009) proved that the integration of organic and inorganic fertilizers is leading to the higher yield due to a more balanced nutrient supply and enhanced potential N availability.

Nonetheless, the highest yield in Vihiga is comparable to the lowest yield at treatment T2 in Nyalgunga. The differences between the maize yields at the three locations are most likely explained by the different soil texture and soil types. In Vihiga, where the maize yield shows the lowest average values, the clay content is the lowest and the texture class is defined as sandy clay loam. In the two locations in Siaya the dominant texture class is sandy clay with an average clay content of approximately 40%, that is around 10% higher than in Vihiga. Besides the texture, different soil classes in Siaya and Vihiga could cause uneven yield distribution between the locations. Sileshi et al. (2010) compared studies and results of maize grown on different soil types among SSA and reported that the soil types do have an influence on the yield. The maize yield was significantly higher on Nitosols and Ferralsols compared to Acrisols. The differences were especially significant on control plots but also occurred on plots treated with inorganic fertilizers. The main soil type in Vihiga is Acrisol and in Siaha Nitisol. Another explanation for the site variation could be an uneven infestation with the parasitic weed *Striga* spp. Kanampiu et al. (2002) estimated that 76% of the area in western Kenya planted to maize and sorghum, is affected by *Striga* spp. However, Vihiga tends to be less infested by *Striga* spp. due to the lower temperature (Odendo et al., 2010).

6.4 Soil Texture and soil fertility

Its is widely accepted that the soil clay content is improving soil fertility due to higher cation exchange capacity and plant available water due to superior water holding capacity. Reuter (1994) and Ismail and Ozawa (2007) even suggested clay application to improve some physical soil properties and hence to increase yield.

The results of the topsoil are showing significant differences (p=0,001) between maize yield in connection to the texture class. The mean maize yield on sandy clay loam is 1108 kg/ha where on sandy clay 2273 kg/ha. Although the clay content in Vihiga is lower than in Siaya, 30% clay still seems to be relatively high and raises the question if the clay content alone is responsible for that low yield in Vihiga. It is well know that tropical soils do often contain low activity clay (LAC) and are less fertile. The distribution between high and low activity clays and oxides in case of this study is uncertain. Further investigations on soil mineralogy and oxides are needed to explain the influence of the soil texture on the yield.

6.5 Infiltration rate

The variation between the results seems to be common for tropical soils. Other research (Wilkinson and Aina, 1976 and Moroke et al., 2009) shows IF in the range between 0.05 and 0.4 cm/min, what is comparable to the results in this study (0.09 to 0.63 cm/min). The differences in IF between the farms are very likely to be explained by the different soil texture. Although statistically not significant, the mean IF on sandy clay loam, as in Vihiga, is approximately 0.1 cm/min lower than on sandy clay. Further the data indicates slightly higher IF values in Siaya than in Vihiga. As well as for the maize yield, the farm SI/Y1/C3 is showing a lower IF value than other farms in Siaya. A possible explanation might be that due to the destroyed crop, the root system was less developed and hence the soil was less porous. Furthermore, the BD at this farm shows slightly higher values. It is well known that an increase in BD is reducing IF.

6.6 Bulk density

The data shows a slightly higher BD on sandy clay loam soils, than on sandy clay soils. It is generally accepted that the BD tends to be higher in sandy soils than in the fine-textured soil, due to the lower organic matter content and less aggregation. Further, all BD values are within the, by Pierce et al. (1983) recommended, limit for root growth (1.49 g/cm³ for soils containing 35 to 45% clay).

In general, the rather low BD in the topsoil can be explained by the ploughing that occurred twice a year during the duration of the study. Nevertheless, Etana et al., (1999) and Alakukku, (1998) reported an increase in BD on fine-textured soils below the tillage depth. Further investigations on the BD in deeper layers are necessary to estimate the compaction of the soil as a restricting factor to root growth and further maize yield.

The results do not show any differences between the treatments, what is contrary to the findings of other studies. Celik et al. (2010) and Zebarth et al. (1999) reported a decline in BD after long-term application of organic fertilizers. An explanation for that might be the poor quality of FYM (see 6.7).

6.7 Organic carbon content in soil

As hypothesized, the treatment does have an influence on the OC. The OC in treatment T5 is significantly higher than in the control treatment T2. Surprisingly, the treatment T4 which was fertilized with FYM does not show any differences to T2. This may indicate that mineral fertilizers have a higher effect on OC than organic fertilizers. However other studies (Celik et al., 2010; Enghball, 2002 and Shisanya et al., 2009) reported opposite findings. Where only organic fertilizers contributed to increased OC and mineral fertilizers had none or and indirect effect on OC due to improved yield. Therefore it is more likely that the higher OC in treatment T5 is attributable to the higher yield and higher biomass production in the root zone. Another reason for the lacking improvement of OC after application of organic amendments, might be the poor quality of FYM among the farms. Vanlauwe and Giller (2006) recognized that FYM had a medium to low quality material and Odendo et al. (2010) recognized out that farmers do complain about low technical know-how on suitable soil fertility practices. Treatment T4 and T5 were fertilized with local FYM, that differed between farms and cropping season from each other in their composition and quality.

The differences in OC between the locations are most likely explained by the different clay content. It is generally accepted that the soil C is increasing with the clay content. This trend was also realized for tropical LAC soils (Feller and Beare, 1997).

6.8 Aggregate stability

It was expected that the AS will increase with a higher OC content. The data in Nyabeda and Vihiga indicates a higher AS in treatment T4, which is fertilized with FYM, than in the control treatment T2. However these results are statistically not significant. Further, it seems interesting to mention that the OC content does not show higher values among T4 in comparison to treatment T2. The OC is higher among the best fertilized treatment T5, but here the AS shows lower values than in T4. This may indicate that mineral fertilizers have a negative or neutral impact on the AS. Other studies (Yu et al, 2012 and Huang et al, 2010) showed that mineral fertilizers did not affect AS despite the increased OC, but organic amendments did.

The results in Nyalgunga are against all expectations. The AS, with a highest mean value on treatment T2, followed by T4 and T5, could lead to the assumption that OC, regardless if from mineral or organic source, has nor or little influence on AS. Barthés et al. (2007) reported that the aggregation in tropical soils, which are dominated by low-activity clays (LAC), is rather affected by Al-containing sesquioxides than by OC. Hence, the positive correlation between AS and OC, showed by other studies (Herencia et al., 2011 and Dunjana et al., 2012), might not be that relevant for tropical soils.

The variability of the results within one treatment may be explained by the different soil texture among the locations. The AS is significantly higher (p=0.048) on sandy clay than on sandy clay loam, with mean values of 43.5% and 35.6%, respectively. This finding is consensual with the general knowledge that the clay content has a positive effect on AS (Amézketa, 1999).

Nevertheless, some facts as for example (1) the high variability of the results (15.3 to 79.2 %), (2) the unexpected trends between the treatments and (3) especially the confusing results from Nyalgunga, lead to the concern that the laboratory analysis might be incorrect. Another possible explanation might be an inadequate management of the trails during the study period. A repetition of the analyses in another laboratory would be necessary to exclude the above mentioned possibilities and verify the data of this study.

7. Conclusion

This study showed only partly that long term fertilizer application has an effect on physical properties. IF and BD were not influenced by, nether organic or inorganic fertilizers. Effects were found on AS, that seem to be positive affected by organic fertilizers. Further, this study indicates that mineral fertilizers contribute more to the increase of OC than organic fertilizers.

The results indicated that OC might not be that important for AS as other studies reported. An increase in OC due to mineral fertilizer did not resulting in higher AS. Further, literature suggests Al-containing sesquioxides as a main driver of aggregation in tropical soils. IF and BD were not influenced by OC.

The best treatment for optimal maize growth is a combination of farmyard manure, Mavuno fertilizer and top dressing. FYM alone is improving the yield in comparison to no treatment at all. Nevertheless, organic and mineral fertilizers can increase maize yield just to a certain extent. The texture classes and hence the clay content, play an important role for agricultural productivity. The highest yields were found on sandy clay soils with combined organic and mineral fertilizer treatment. Further, the soil types affected maize yield. Highest yields occurred on Nitisols and lowest yields occured on Acrisols. The dependency on the soil texture and soil type indicates that the choice of a suitable cropping site can be more important and sustainable than the treatment with fertilizers itself. Other physical soil parameters (IF, BD, AS) did not influence maize yield.

The results did not indicate any differences between high and low fertility plots, nether in maize yield nor in any of the physical soil properties. It is very likely that the differences between the plots were settled during the long-term treatment during the eight years of the study. Hence, long-term fertilizer application is not suitable to study differences in soil fertility gradients.

The rainfall amount is able to cover the water crop requirements of maize in all locations. The negative water balance during late stage might even be beneficial for maize storage due to the lower grain moisture at the harvest. Nevertheless, these results should be seen as a rough estimation. Further research on the water holding capacity of soils is recommended.

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9. References

Alakukku, L. (1998). Properties of compacted fine-textured soils as affected by crop rotation and reduced tillage. *Soil and Tillage Research* 47(1–2), 83–89.

Amézketa E. (1999). Soil aggregate stability: A review. *Journal of Sustainable Agriculture* 14, 83–151.

Barthès, B. G., Kouakoua, E., Larré-Larrouy, M.-C., Razafimbelo, T. M., De Luca, E. F., Azontonde, A., Neves, C. S. V. J., De Freitas, P. L. & Feller, C. L. (2008). Texture and sesquioxide effects on water-stable aggregates and organic matter in some tropical soils. *Geoderma* 143(1–2), 14–25.

Celik, I., Gunal, H., Budak, M. & Akpinar, C. (2010). Effects of long-term organic and mineral fertilizers on bulk density and penetration resistance in semi-arid Mediterranean soil conditions. *Geoderma* 160(2), 236–243.

CountrySTAT - Kenya. *Population in Census Years*. [online] (2013). Available from: http://www.countrystat.org/home.aspx?c=KEN&ta=114CPO010&tr=12. [Accessed 2013-01-07].

Donovan, W. G. & Casey, F. (1998). *Soil fertility management in sub-Saharan Africa*. World Bank Publications. ISBN 9780821342367.

Drechsel, P., Gyiele, L., Kunze, D. & Cofie, O. (2001). Population density, soil nutrient depletion, and economic growth in sub-Saharan Africa. *Ecological Economics* 38(2), 251–258.

Dunjana, N., Nyamugafata, P., Shumba, A., Nyamangara, J. & Zingore, S. (2012). Effects of cattle manure on selected soil physical properties of smallholder farms on two soils of Murewa, Zimbabwe. *Soil Use and Management* no–no.

Eghball, B. (2002). Soil properties as influenced by phosphorus- and nitrogen-based manure and compost applications. *Agronomy Journal* 94(1), 128–135.

Etana, A., Håkansson, I., Zagal, E. & Bučas, S. (1999). Effects of tillage depth on organic carbon content and physical properties in five Swedish soils. *Soil and Tillage Research* 52(3–4), 129–139.

FAO. *Crop evapotranspiration, Chapter 6 - ETc - Single crop coefficient (Kc)*. [online] (1998). Available from: http://www.fao.org/docrep/X0490E/x0490e0b.htm#length%20of%20growth%20stages. [Accessed 2012-09-27].

FAO (2006a). Guidelines for Soil Description. [online],. Available from: ftp://ftp.fao.org/agl/agll/docs/guidel_soil_descr.pdf. [Accessed 2012-09-27].

FAO (2006b). *World reference base for soil resources 2006* [online]. Available from: ftp://ftp.fao.org/agl/agll/docs/wsrr103e.pdf. [Accessed 2012-12-10].

FAO. *FAOSTAT*. [online] (2010). Available from: http://faostat.fao.org/. [Accessed 2012-06-19].

FAO WATER. *ClimWat - Water Development and Management Unit - Information Resources - Databases*. [online] (2012). Available from: http://www.fao.org/nr/water/infores_databases_climwat.html. [Accessed 2012-09-27].

Feller, C. & Beare, M. H. (1997). Physical control of soil organic matter dynamics in the tropics. *Geoderma* 79(1–4), 69–116.

Franzluebbers, A. . (2002). Water infiltration and soil structure related to organic matter and its stratification with depth. *Soil and Tillage Research* 66(2), 197–205.

Gao, Y., Duan, A., Sun, J., Li, F., Liu, Z., Liu, H. & Liu, Z. (2009). Crop coefficient and water-use efficiency of winter wheat/spring maize strip intercropping. *Field Crops Research* 111(1–2), 65–73.

Gentile, R., Vanlauwe, B., Chivenge, P. & Six, J. (2008). Interactive effects from combining fertilizer and organic residue inputs on nitrogen transformations. *Soil Biology and Biochemistry* 40(9), 2375–2384.

Google. *Google Maps*. [online] (2012). Available from: https://maps.google.se/. [Accessed 2012-07-11].

Hati, K. M., Swarup, A., Mishra, B., Manna, M. C., Wanjari, R. H., Mandal, K. G. & Misra, A. K. (2008). Impact of long-term application of fertilizer, manure and lime under intensive cropping on physical properties and organic carbon content of an Alfisol. *Geoderma* 148(2), 173–179.

Herencia, J. F., García-Galavís, P. A. & Maqueda, C. (2011). Long-Term Effect of Organic and Mineral Fertilization on Soil Physical Properties Under Greenhouse and Outdoor Management Practices. *Pedosphere* 21(4), 443–453.

Huang, S., Peng, X., Huang, Q. & Zhang, W. (2010). Soil aggregation and organic carbon fractions affected by long-term fertilization in a red soil of subtropical China. *Geoderma* 154(3-4), 364–369.

Ismail, S. M. & Ozawa, K. (2007). Improvement of crop yield, soil moisture distribution and water use efficiency in sandy soils by clay application. *Applied Clay Science* 37(1–2), 81–89.

Jaetzold R., Schmidt H., Hornet B. & Shisanya C. (2005). Farm Management Handbook: Natural Conditions and Farm Management Information. [online],. Available from: http://www2.gtz.de/dokumente/bib/07-1282.pdf. [Accessed 2012-06-06].

Kanampiu F., Friesen D. & Gressel J. (2002). CIMMYT unveils herbicide-coated maize seed technology for Strica control. *Haustorium* 42, 1-3.

Kang, S., Gu, B., Du, T. & Zhang, J. (2003). Crop coefficient and ratio of transpiration to evapotranspiration of winter wheat and maize in a semi-humid region. *Agricultural Water Management* 59(3), 239–254.

Kenya Soil Survey. *Agro-Climatic Zone Map of Kenya*. [online] (1980a). Available from: http://eusoils.jrc.ec.europa.eu/esdb_archive/eudasm/africa/images/maps/download/afr_ke acz2.jpg. [Accessed 2012-11-21].

Kenya Soil Survey. *Explatory Soil Map of Kenya*. [online] (1980b). Available from: http://eusoils.jrc.ec.europa.eu/esdb_archive/eudasm/africa/images/maps/download/afr_ke esm.jpg. [Accessed 2012-11-21].

Khan, Z. R., Midega, C. A. O., Amudavi, D. M., Hassanali, A. & Pickett, J. A. (2008). On-farm evaluation of the 'push–pull' technology for the control of stemborers and striga weed on maize in western Kenya. *Field Crops Research* 106(3), 224–233.

Moroke, T. S., Dikinya, O. & Patrick, C. (2009). Comparative assessment of water infiltration of soils under different tillage systems in eastern Botswana. *Physics and Chemistry of the Earth, Parts A/B/C* 34(4–5), 316–323.

Odendo, Groote, H. & Odongo, O.M. (2001). Assessment of farmers' preferences and constraints to maize production in the moist Mid-altitude zone of western Kenya. *African Crop Science Assiociation* ACSA (Eds.), African Crop Science Conference Proceedings, 769–775.

Odendo, M., Obare, G. & Salasya, B. (2010). Farmers' perceptions and knowledge of soil fertility degradation in two contrasting sites in western Kenya. *Land Degradation & Development* 21(6), 557–564.

Oswald, A. (2005). Striga control—technologies and their dissemination. *Crop Protection* 24(4), 333–342.

Pierce, F. J., Larson, W. E., Dowdy, R. H. & Graham, W. A. P. (1983). Productivity of soils: assessing long-term changes due to erosion. *Journal of Soil & Water Conservation* 38(1), 39–44.

Pinitpaitoon, S., Suwanarit, A. & Bell, R. W. (2011). A framework for determining the efficient combination of organic materials and mineral fertilizer applied in maize cropping. *Field Crops Research* 124(3), 302–315.

Place, F., Barrett, C. B., Freeman, H. A., Ramisch, J. J. & Vanlauwe, B. (2003). Prospects for integrated soil fertility management using organic and inorganic inputs: evidence from smallholder African agricultural systems. *Food Policy* 28(4), 365–378.

Rasool, R., Kukal, S. S. & Hira, G. S. (2008). Soil organic carbon and physical properties as affected by long-term application of FYM and inorganic fertilizers in maize–wheat system. *Soil and Tillage Research* 101(1–2), 31–36.

Reuter, G. (1994). Improvement of sandy soils by clay-substrate application. *Applied Clay Science* 9(2), 107–120.

Rosegrant M.W., Msangi S., Ringler C., Sulser T.B., Zhu T. & Cline S.A. (2008). International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT): Model Description. *International Food Policy Research Institute, Washington D.C.* [online],. Available from: http://www.ifpri.org/themes/impact/impactwater.pdf. [Accessed 2012-05-01].

Sanchez, P. A. (2002). Soil fertility and hunger in Africa. *Science* 295(5562), 2019–2020.

Sauerborn, J. (1991). Parasitic flowering plants: ecology and management. [online],. Available from: http://www.cabdirect.org/abstracts/19922325777.html;jsessionid=1FE9E40BCB37BAA8599F 302A61A2B3E0?freeview=true. [Accessed 2012-11-28].

Shepherd, K. D. & Soule, M. J. (1998). Soil fertility management in west Kenya: dynamic simulation of productivity, profitability and sustainability at different resource endowment levels. *Agriculture Ecosystems & Environment* 71(1-3), 131–145.

Shisanya, C. A., Mucheru, M. W., Mugendi, D. N. & Kung'u, J. B. (2009). Effect of organic and inorganic nutrient sources on soil mineral nitrogen and maize yields in central highlands of Kenya. *Soil and Tillage Research* 103(2), 239–246.

Sileshi, G., Akinnifesi, F. K., Debusho, L. K., Beedy, T., Ajayi, O. C. & Mong'omba, S. (2010). Variation in maize yield gaps with plant nutrient inputs, soil type and climate across sub-Saharan Africa. *Field Crops Research* 116(1–2), 1–13.

Tittonell, P., Vanlauwe, B., Leffelaar, P. A., Rowe, E. C. & Giller, K. E. (2005). Exploring diversity in soil fertility management of smallholder farms in western Kenya: I. Heterogeneity at region and farm scale. *Agriculture, Ecosystems & Environment* 110(3–4), 149–165.

Vanlauwe, B. & Giller, K. (2006). Popular myths around soil fertility management in sub-Saharan Africa. *Agriculture, Ecosystems & Environment* 116(1-2), 34–46.

Vanlauwe, B., Kanampiu, F., Odhiambo, G. D., De Groote, H., Wadhams, L. J. & Khan, Z. R. (2008). Integrated management of Striga hermonthica, stemborers, and declining soil fertility in western Kenya. *Field Crops Research* 107(2), 102–115.

Vanlauwe, B., Tittonell, P. & Mukalama, J. (2006). Within-farm soil fertility gradients affect response of maize to fertiliser application in western Kenya. *Nutrient Cycling in Agroecosystems* 76(2), 171–182.

Vanlauwe, B. (2004). Integrated soil fertility management research at TSBF: the framework, the principles and their application. *Academy Science Publishers* A. Bationo (Ed.), Managing Nutrient Cycles to Sustain Soil Fertility in sub-Saharan Africa, 25–42.

Walkley, A. (1946). A critical examination of a rapid method for determination, organic carbon in soils: effects of variations in digestion conditious and organic soils constituints. *Soil Science* (63), 251–263.

Watson, C. a., Atkinson, D., Gosling, P., Jackson, L. r. & Rayns, F. w. (2002). Managing soil fertility in organic farming systems. *Soil Use and Management* 18, 239–247.

Wikipedia. *Map of Kenya*. [online] (2011). Available from: http://en.wikipedia.org/wiki/File:Western_in_Kenya.svg. [Accessed 2013-01-07].

Wilkinson, G. E. & Aina, P. O. (1976). Infiltration of water into two nigerian soils under secondary forest and subsequent arable cropping. *Geoderma* 15(1), 51–59.

Yoder, R.E. (1936). A direct method of aggregate analysis of soils and a study of the physical nature of erosion losses. *J. Am. Soc. Agron.* 28, 337–351.

Yu, H., Ding, W., Luo, J., Geng, R. & Cai, Z. (2012). Long-term application of organic manure and mineral fertilizers on aggregation and aggregate-associated carbon in a sandy loam soil. *Soil and Tillage Research* 124(0), 170–177.

Zebarth, B. J., Neilsen, G. H., Hogue, E. & Neilsen, D. (1999). Influence of organic waste amendments on selected soil physical and chemical properties. *Canadian Journal of Soil Science* 79(3), 501–504.

Zingore, S., Murwira, H. K., Delve, R. J. & Giller, K. E. (2007). Influence of nutrient management strategies on variability of soil fertility, crop yields and nutrient balances on smallholder farms in Zimbabwe. *Agriculture, Ecosystems & Environment* 119(1–2), 112–126.

10. Appendices

Appendix 1. Total annual rainfall in mm during the duration of the project from 1998 to 2011

year	Nyalgunga				Nyabeda					Vihiga		
	SI/Y1/B1	SI/Y1/B2	SI/Y1/C1	SI/Y1/C3	SI/Y2/A1	SI/Y2/A2	SI/Y2/B2	SI/Y2/C2	VI/Y2/0	VI/Y2/A3	VI/Y2/B1	VI/Y2/C1
1998	1908	1908	1709	1908	1908	1908	1908	1908	1969	1969	1969	1969
1999	2104	2104	1893	2104	2104	2104	2104	2104	2043	2043	2043	2043
2000	1723	1723	1538	1723	1723	1723	1723	1723	1699	1699	1699	1699
2001	1873	1873	1713	1873	1873	1873	1873	1873	1874	1874	1874	1874
2002	2000	2000	1802	2000	2000	2000	2000	2000	1983	1983	1983	1983
2003	1811	1811	1687	1811	1811	1811	1811	1811	1727	1727	1727	1727
2004	1595	1595	1479	1595	1595	1595	1595	1595	1612	1612	1612	1612
2005	1485	1485	1408	1485	1485	1485	1485	1485	1437	1437	1437	1437
2006	2668	2668	2358	2668	2668	2668	2668	2668	2573	2573	2573	2573
2007	1782	1782	1659	1782	1782	1782	1782	1782	1874	1874	1874	1874
2008	1982	1982	1800	1982	1982	1982	1982	1982	1978	1978	1978	1978
2009	1712	1712	1542	1712	1712	1712	1712	1712	1797	1797	1797	1797
2010	1868	1868	1598	1868	1868	1868	1868	1868	2097	2097	2097	2097
2011	2024	2024	1691	2024	2024	2024	2024	2024	2087	2087	2087	2087
Mean	**1895**	**1895**	**1705**	**1895**	**1895**	**1895**	**1895**	**1895**	**1911**	**1911**	**1911**	**1911**

Appendix 2. Total Results of the maize yield, soil physical soil properties and organic carbon content in the soil

Location	Farm	Fertility Level	Treat-ment	Maize yield [kg/ha]	Aggregate stability [%]	Soil Organic Carbon [%]	Clay [%]	Sand [%]	Silt [%]	Texture class	Infiltration rate [cm/min]	Bulk density [g/cm³]
Nyalgunga	SI/Y1/B1	H	T2	2533.0	55.09	1.10	39.6	48.4	12.0	sandy clay		
Nyalgunga	SI/Y1/B1	H	T4	2863.2		1.24	41.6	46.4	12.0	sandy clay		
Nyalgunga	SI/Y1/B1	H	T5	4426.9	15.64	1.83	41.6	46.4	12.0	sandy clay		
Nyalgunga	SI/Y1/B1	L	T2	820.7	55.09	1.10	41.6	48.4	10.0	sandy clay		
Nyalgunga	SI/Y1/B1	L	T4	2537.8	57.31	1.17	45.6	46.5	8.0	sandy clay		
Nyalgunga	SI/Y1/B1	L	T5	5119.1	39.00	2.17	66.4	16.1	17.5	clay		
Nyalgunga	SI/Y1/B2	H	T2	972.7	17.91	1.66	31.6	58.4	10.0	sandy clay loam	0.27	1.21
Nyalgunga	SI/Y1/B2	H	T4	2700.9	17.27	1.37	27.6	62.4	10.0	sandy clay loam		1.13
Nyalgunga	SI/Y1/B2	H	T5	2730.9	79.22	2.47	29.6	60.5	10.0	sandy clay loam	0.47	1.27
Nyalgunga	SI/Y1/B2	L	T2	2508.5	34.11	1.29	37.6	50.4	12.0	sandy clay	0.47	1.09
Nyalgunga	SI/Y1/B2	L	T4	4479.0	28.10	1.13	39.6	48.4	12.0	sandy clay		1.10
Nyalgunga	SI/Y1/B2	L	T5	6536.2	22.21	2.13	37.6	50.4	12.0	sandy clay	0.40	1.12
Nyalgunga	SI/Y1/C1	H	T2	1475.1	42.96	0.83	43.6	44.5	12.0	clay	0.57	1.20
Nyalgunga	SI/Y1/C1	H	T4	2219.4	39.79	1.03	37.6	50.4	12.0	sandy clay		1.11
Nyalgunga	SI/Y1/C1	H	T5	2805.7	35.52	1.65	60.4	24.0	15.6	clay	0.55	1.14
Nyalgunga	SI/Y1/C1	L	T2	2574.3	31.11	1.01	39.6	48.4	12.0	sandy clay	0.61	1.23
Nyalgunga	SI/Y1/C1	L	T4	4729.1		0.77	43.6	48.4	8.0	sandy clay		1.07
Nyalgunga	SI/Y1/C1	L	T5	4252.8		1.61	41.6	48.4	10.0	sandy clay	0.48	1.20
Nyalgunga	SI/Y1/C3	H	T2	51.8	34.97	0.92	33.6	54.4	12.0	sandy clay loam	0.09	1.06
Nyalgunga	SI/Y1/C3	H	T4	643.8	26.45	0.90	29.6	54.4	16.0	sandy clay loam		1.32
Nyalgunga	SI/Y1/C3	H	T5	164.9	40.16	1.50	35.6	52.4	12.0	sandy clay	0.27	1.21
Nyalgunga	SI/Y1/C3	L	T2		45.94	0.83	41.6	48.4	10.0	sandy clay	0.23	1.23
Nyalgunga	SI/Y1/C3	L	T4		44.30	0.83	39.6	50.4	10.0	sandy clay		1.19
Nyalgunga	SI/Y1/C3	L	T5		16.38	1.91	35.6	52.5	12.0	sandy clay	0.23	1.16
Nyabeda	SI/Y2/A1	H	T2	743.6	47.01	1.61	41.6	46.4	12.0	sandy clay	0.63	1.14
Nyabeda	SI/Y2/A1	H	T4	3579.5		1.71	41.6	46.4	12.0	sandy clay		1.14
Nyabeda	SI/Y2/A1	H	T5	2487.0		2.28	41.6	46.4	12.0	sandy clay	0.60	1.11
Nyabeda	SI/Y2/A1	L	T2	1450.8	59.60	2.03	41.5	46.5	12.0	sandy clay	0.57	1.03
Nyabeda	SI/Y2/A1	L	T4	1225.0	43.07	1.39	43.6	46.4	10.0	sandy clay		1.03
Nyabeda	SI/Y2/A1	L	T5	3399.7	36.11	2.25	41.6	46.4	12.0	sandy clay	0.34	1.24

Location	Farm	Fertility Level	Treat-ment	Maize yield [kg/ha]	Aggregate stability [%]	Soil Organic Carbon [%]	Clay [%]	Sand [%]	Silt [%]	Texture class	Infiltration rate [cm/min]	Bulk density [g/cm³]
Nyabeda	SI/Y2/A2	H	T2	1333.3	34.67	1.89	39.6	46.4	14.0	sandy clay		
Nyabeda	SI/Y2/A2	H	T4	1982.6	60.58	2.12	41.6	46.4	12.0	sandy clay		
Nyabeda	SI/Y2/A2	H	T5	3159.6	62.87	2.66	39.6	48.4	12.0	sandy clay		
Nyabeda	SI/Y2/A2	L	T2	1660.8	49.95	1.80	39.6	46.4	14.0	sandy clay		
Nyabeda	SI/Y2/A2	L	T4	1143.4	56.92	1.75	41.6	46.4	12.0	sandy clay		
Nyabeda	SI/Y2/A2	L	T5	3259.1	39.30	2.58	39.6	46.4	14.0	sandy clay		
Nyabeda	SI/Y2/B2	H	T2	1273.7		1.34	37.6	48.4	14.0	sandy clay	0.42	1.14
Nyabeda	SI/Y2/B2	H	T4	2922.0	51.26	1.41	21.6	70.4	8.0	sandy clay loam		1.20
Nyabeda	SI/Y2/B2	H	T5	2629.1	50.00	2.02	35.6	50.5	14.0	sandy clay	0.53	1.18
Nyabeda	SI/Y2/B2	L	T2	1326.2	34.99	1.29	39.6	48.4	12.0	sandy clay	0.50	1.22
Nyabeda	SI/Y2/B2	L	T4	1879.3	61.70	1.52	37.5	48.5	14.0	sandy class		1.16
Nyabeda	SI/Y2/B2	L	T5	2096.9		2.13	58.4	22.0	19.5	clay	0.33	1.19
Nyabeda	SI/Y2/C2	H	T2	479.0	49.02	1.61	43.6	44.4	12.0	clay	0.27	1.06
Nyabeda	SI/Y2/C2	H	T4	335.3	37.61	1.54	39.5	46.5	14.0	sandy clay		1.16
Nyabeda	SI/Y2/C2	H	T5	2080.7	37.84	2.13	37.6	50.4	12.0	sandy clay	0.28	1.02
Nyabeda	SI/Y2/C2	L	T2	80.2		1.80	39.6	46.4	14.0	sandy clay	0.21	1.09
Nyabeda	SI/Y2/C2	L	T4	512.8	56.74	1.43	41.5	48.5	10.0	sandy clay		1.15
Nyabeda	SI/Y2/C2	L	T5	2205.3	42.14	2.10	39.6	48.4	12.0	sandy clay	0.23	1.03
Vihiga	VI/Y2/0	H	T2	158.8	23.25	0.64	25.6	68.4	6.0	sandy clay loam		
Vihiga	VI/Y2/0	H	T4	892.7	39.98	1.13	27.6	64.4	8.0	sandy clay loam		
Vihiga	VI/Y2/0	H	T5	1508.7	34.48	1.53	34.7	53.7	11.6	sandy clay loam		
Vihiga	VI/Y2/0	L	T2	481.1	51.51	1.24	29.6	56.4	14.0	sandy clay loam		
Vihiga	VI/Y2/0	L	T4	1333.0	42.39	1.35	29.6	60.4	10.0	sandy clay loam		
Vihiga	VI/Y2/0	L	T5	2177.1	15.26	2.02	31.6	58.4	10.0	sandy clay loam		
Vihiga	VI/Y2/A3	H	T2	3.8	24.01	1.15	31.6	56.4	12.0	sandy clay loam		
Vihiga	VI/Y2/A3	H	T4	584.4	41.06	1.32	29.6	56.4	14.0	sandy clay loam		
Vihiga	VI/Y2/A3	H	T5	1063.7		2.10	33.6	56.4	10.0	sandy clay loam		
Vihiga	VI/Y2/A3	L	T2	164.3	32.42	1.34	33.6	56.4	10.0	sandy clay loam		
Vihiga	VI/Y2/A3	L	T4	76.2	48.52	1.58	33.5	56.5	10.0	sandy clay loam		
Vihiga	VI/Y2/A3	L	T5	1945.7	35.40	2.36	31.6	56.4	12.0	sandy clay loam		
Vihiga	VI/Y2/B1	H	T2	163.3	30.75	1.29	29.6	60.4	10.0	sandy clay loam	0.30	1.19
Vihiga	VI/Y2/B1	H	T4	685.3	33.79	1.13	31.6	60.4	8.0	sandy clay loam		1.22

Location	Farm	Fertility Level	Treat-ment	Maize yield [kg/ha]	Aggregate stability [%]	Soil Organic Carbon [%]	Clay [%]	Sand [%]	Silt [%]	Texture class	Infiltration rate [cm/min]	Bulk density [g/cm³]
Vihiga	VI/Y2/B1	H	T5	1451.2	37.40	1.98	29.6	60.4	10.0	sandy clay loam	0.43	1.17
Vihiga	VI/Y2/B1	L	T2	483.9	31.38	1.43	29.6	60.4	10.0	sandy clay loam	0.33	1.19
Vihiga	VI/Y2/B1	L	T4	2332.8	50.43	1.69	31.6	60.4	8.0	sandy clay loam		1.25
Vihiga	VI/Y2/B1	L	T5	1234.1	45.66	1.98	21.6	66.4	12.0	sandy clay loam	0.29	1.22
Vihiga	VI/Y2/C1	H	T2	728.0	35.91	1.38	31.6	54.4	14.0	sandy clay loam		
Vihiga	VI/Y2/C1	H	T4	957.3	45.13	1.30	31.6	56.4	12.0	sandy clay loam		
Vihiga	VI/Y2/C1	H	T5	1170.1	56.29	2.17	35.6	54.5	10.0	sandy clay		
Vihiga	VI/Y2/C1	L	T2	610.0	31.09	1.10	29.6	58.4	12.0	sandy clay loam		
Vihiga	VI/Y2/C1	L	T4	928.7	48.96	1.07	33.6	58.4	8.0	sandy clay loam		
Vihiga	VI/Y2/C1	L	T5	2137.6		2.21	33.6	56.4	10.0	sandy clay loam		

Appendix 3. Total results of the Crop Evapotranspiration and Water Balance

Crop stage	Day	Nyalgunga			Nyabeda			Vihiga		
		Rainfall [mm/d]	ETc [mm/d]	Water Balance [mm/d]	Rainfall [mm/d]	ETc [mm/d]	Water Balance [mm/d]	Rainfall [mm/d]	ETc [mm/d]	Water Balance [mm/d]
initial	1	0.00	2.44	-2.44	10.25	2.33	7.92	2.56	3.95	-1.39
	2	0.00	2.44	-2.44	0.00	2.33	-2.33	1.60	3.95	-2.35
	3	0.00	2.44	-2.44	0.00	2.33	-2.33	0.00	3.95	-3.95
	4	0.00	2.44	-2.44	0.00	2.33	-2.33	7.61	3.95	3.66
	5	11.90	2.44	9.45	0.00	2.33	-2.33	20.69	3.95	16.74
	6	13.93	2.44	11.49	11.76	2.33	9.43	0.49	3.95	-3.46
	7	0.00	2.44	-2.44	18.58	2.33	16.25	0.00	3.95	-3.95
	8	0.00	2.44	-2.44	0.00	2.33	-2.33	0.00	3.95	-3.95
	9	0.29	2.44	-2.16	0.00	2.33	-2.33	0.00	3.95	-3.95
	10	0.00	2.44	-2.44	0.00	2.33	-2.33	7.07	3.95	3.12
	11	12.50	2.44	10.06	0.00	2.33	-2.33	5.03	3.95	1.08
	12	2.89	2.44	0.45	15.19	2.33	12.86	0.00	3.95	-3.95
	13	0.00	2.44	-2.44	3.86	2.33	1.53	21.07	3.95	17.12
	14	7.13	2.44	4.69	0.00	2.33	-2.33	2.66	3.95	-1.29
	15	1.45	2.44	-0.99	9.51	2.33	7.18	9.68	3.95	5.73
	16	11.31	2.44	8.87	0.68	2.33	-1.65	17.40	3.95	13.45
	17	27.08	2.44	24.64	11.21	2.33	8.88	4.38	3.95	0.43
	18	11.25	2.44	8.80	26.73	2.33	24.40	2.60	4.13	-1.53
	19	0.37	2.62	-2.25	10.27	2.33	7.94	12.85	4.13	8.72
	20	8.56	2.62	5.94	0.00	2.50	-2.50	13.47	4.13	9.34
development	21	10.08	2.68	7.40	6.51	2.56	3.95	0.00	4.13	-4.13
	22	3.25	2.74	0.51	12.13	2.62	9.51	13.47	4.13	9.34
	23	17.08	2.80	14.28	4.33	2.68	1.65	26.91	4.13	22.78
	24	10.88	2.86	8.03	21.35	2.75	18.60	0.00	4.13	-4.13
	25	0.00	2.91	-2.91	12.06	2.81	9.25	0.00	4.13	-4.13
	26	0.00	2.97	-2.97	0.00	2.87	-2.87	0.00	4.13	-4.13
	27	0.00	3.03	-3.03	0.00	2.93	-2.93	5.86	4.14	1.72
	28	0.00	3.09	-3.09	0.00	2.99	-2.99	0.00	4.14	-4.14
	29	1.36	3.15	-1.79	0.00	3.06	-3.06	0.00	4.14	-4.14

| Crop stage | Day | Nyalgunga | | | Nyabeda | | | Vihiga | | |
		Rainfall [mm/d]	ETc [mm/d]	Water Balance [mm/d]	Rainfall [mm/d]	ETc [mm/d]	Water Balance [mm/d]	Rainfall [mm/d]	ETc [mm/d]	Water Balance [mm/d]
development	30	0.00	3.21	-3.21	1.65	3.12	-1.47	9.24	4.14	5.10
	31	23.34	3.27	20.07	0.00	3.18	-3.18	9.32	4.14	5.18
	32	20.51	3.33	17.19	22.77	3.24	19.53	11.34	4.14	7.20
	33	6.98	3.39	3.60	18.77	3.31	15.46	0.00	4.15	-4.15
	34	0.20	3.44	-3.24	8.99	3.37	5.62	0.00	4.15	-4.15
	35	5.51	3.50	2.01	0.00	3.43	-3.43	0.98	4.15	-3.17
	36	20.43	3.56	16.87	2.58	3.49	-0.91	51.95	4.15	47.80
	37	16.74	3.62	13.12	7.77	3.56	4.21	0.77	4.15	-3.38
	38	0.00	3.68	-3.68	20.39	3.62	16.77	0.68	4.15	-3.47
	39	0.00	3.74	-3.74	0.00	3.68	-3.68	0.00	4.16	-4.16
	40	1.81	3.80	-1.99	0.00	3.74	-3.74	0.00	4.16	-4.16
	41	0.00	3.86	-3.86	2.41	3.81	-1.40	8.29	4.16	4.13
	42	9.20	3.91	5.29	0.00	3.87	-3.87	3.79	4.16	-0.37
	43	1.71	3.97	-2.26	7.80	3.93	3.87	8.32	4.16	4.16
	44	2.08	4.03	-1.95	2.28	3.99	-1.71	13.47	4.16	9.31
	45	7.78	4.09	3.68	2.08	4.05	-1.97	2.16	4.16	-2.00
	46	3.90	4.15	-0.25	8.56	4.12	4.44	7.96	4.17	3.79
	47	11.40	4.21	7.19	4.99	4.18	0.81	2.66	4.17	-1.51
	48	7.11	4.27	2.85	12.79	4.24	8.55	0.00	4.17	-4.17
	49	2.94	4.33	-1.38	8.06	4.30	3.76	29.90	3.96	25.94
	50	38.05	4.56	33.48	3.01	4.37	-1.36	36.44	3.96	32.48
	51	4.99	4.63	0.36	42.95	4.61	38.34	81.35	3.97	77.38
	52	56.93	4.69	52.24	6.31	4.67	1.64	4.50	3.97	0.53
	53	2.09	4.75	-2.65	69.30	4.74	64.56	12.12	3.97	8.15
	54	33.01	4.81	28.20	2.35	4.80	-2.45	10.51	3.97	6.54
	55	1.61	4.87	-3.26	31.77	4.87	26.90	0.00	3.97	-3.97
mid	56	11.84	4.87	6.97	2.13	4.87	-2.74	17.55	3.97	13.58
	57	5.76	4.87	0.89	13.08	4.87	8.21	11.93	3.97	7.96
	58	15.46	4.87	10.59	4.25	4.87	-0.62	21.82	3.97	17.85
	59	30.96	4.87	26.09	15.46	4.87	10.59	0.00	3.97	-3.97
	60	2.40	4.87	-2.47	29.96	4.87	25.09	7.43	3.97	3.46

Crop stage	Day	Nyalgunga			Nyabeda			Vihiga		
		Rainfall [mm/d]	ETc [mm/d]	Water Balance [mm/d]	Rainfall [mm/d]	ETc [mm/d]	Water Balance [mm/d]	Rainfall [mm/d]	ETc [mm/d]	Water Balance [mm/d]
mid	61	1.88	4.87	-2.99	0.00	4.87	-4.87	0.00	3.97	-3.97
	62	4.12	4.87	-0.75	2.51	4.87	-2.36	2.08	3.97	-1.89
	63	6.33	4.87	1.46	3.74	4.87	-1.13	0.00	3.97	-3.97
	64	0.00	4.87	-4.87	7.86	4.87	2.99	0.00	3.97	-3.97
	65	0.00	4.87	-4.87	0.00	4.87	-4.87	0.00	3.97	-3.97
	66	30.72	4.87	25.85	0.00	4.87	-4.87	3.73	3.97	-0.24
	67	4.27	4.87	-0.60	31.22	4.87	26.35	0.00	3.97	-3.97
	68	0.00	4.87	-4.87	0.00	4.87	-4.87	33.90	3.97	29.93
	69	17.28	4.87	12.41	0.00	4.87	-4.87	16.51	3.97	12.54
	70	6.77	4.87	1.90	20.33	4.87	15.46	5.19	3.97	1.22
	71	7.56	4.87	2.69	8.28	4.87	3.41	16.78	3.97	12.81
	72	12.44	4.87	7.56	5.96	4.87	1.09	13.12	3.97	9.15
	73	52.36	4.87	47.49	14.76	4.87	9.89	5.27	3.97	1.30
	74	4.47	4.87	-0.40	59.86	4.87	54.99	0.00	3.97	-3.97
	75	0.00	4.87	-4.87	4.25	4.87	-0.62	0.54	3.97	-3.43
	76	0.00	4.87	-4.87	0.00	4.87	-4.87	4.12	3.97	0.15
	77	0.00	4.87	-4.87	0.00	4.87	-4.87	23.40	3.97	19.43
	78	12.08	4.87	7.21	0.00	4.87	-4.87	1.54	3.97	-2.43
	79	6.39	4.87	1.52	11.66	4.87	6.79	1.82	4.25	-2.43
	80	0.24	4.78	-4.54	5.54	4.87	0.67	4.15	4.25	-0.10
	81	0.00	4.78	-4.78	0.32	4.78	-4.46	1.35	4.25	-2.90
	82	2.47	4.78	-2.31	0.00	4.78	-4.78	4.91	4.25	0.66
	83	4.02	4.78	-0.76	1.90	4.78	-2.88	3.18	4.25	-1.07
	84	3.38	4.78	-1.41	4.88	4.78	0.10	0.00	4.25	-4.25
	85	12.85	4.78	8.07	4.30	4.78	-0.48	2.45	4.25	-1.80
	86	4.57	4.78	-0.21	9.75	4.78	4.97	0.00	4.25	-4.25
	87	0.00	4.78	-4.78	6.09	4.78	1.31	0.00	4.25	-4.25
	88	0.00	4.78	-4.78	0.00	4.78	-4.78	5.27	4.25	1.02
	89	0.53	4.78	-4.25	0.00	4.78	-4.78	5.07	4.25	0.82
	90	2.22	4.78	-2.56	0.00	4.78	-4.78	5.84	4.25	1.59
	91	3.22	4.78	-1.56	2.96	4.78	-1.82	7.16	4.25	2.91

Crop stage	Day	Nyalgunga			Nyabeda			Vihiga		
		Rainfall [mm/d]	ETc [mm/d]	Water Balance [mm/d]	Rainfall [mm/d]	ETc [mm/d]	Water Balance [mm/d]	Rainfall [mm/d]	ETc [mm/d]	Water Balance [mm/d]
mid	92	0.28	4.78	-4.51	3.38	4.78	-1.40	1.87	4.25	-2.38
	93	2.08	4.78	-2.70	0.00	4.78	-4.78	4.15	4.25	-0.10
	94	4.34	4.78	-0.44	0.66	4.78	-4.12	0.00	4.25	-4.25
	95	1.33	4.78	-3.45	5.79	4.78	1.01	1.45	4.25	-2.80
late	96	0.03	4.69	-4.66	0.56	4.68	-4.12	0.00	4.16	-4.16
	97	7.30	4.60	2.69	0.00	4.59	-4.59	0.00	4.08	-4.08
	98	2.22	4.52	-2.30	8.05	4.49	3.56	0.00	4.00	-4.00
	99	0.00	4.43	-4.43	2.96	4.40	-1.44	1.40	3.92	-2.52
	100	0.00	4.34	-4.34	0.00	4.30	-4.30	0.00	3.84	-3.84
	101	0.00	4.25	-4.25	0.00	4.21	-4.21	0.00	3.76	-3.76
	102	0.00	4.16	-4.16	0.00	4.11	-4.11	0.00	3.68	-3.68
	103	0.00	4.08	-4.08	0.00	4.02	-4.02	0.00	3.59	-3.59
	104	1.42	3.99	-2.56	0.00	3.92	-3.92	13.19	3.51	9.68
	105	3.39	3.90	-0.51	1.90	3.83	-1.93	1.57	3.43	-1.86
	106	0.36	3.81	-3.45	4.52	3.73	0.79	1.52	3.35	-1.83
	107	0.08	3.72	-3.65	0.00	3.64	-3.64	0.00	3.27	-3.27
	108	0.00	3.64	-3.64	0.10	3.54	-3.44	0.00	3.19	-3.19
	109	0.00	3.55	-3.55	0.00	3.45	-3.45	0.00	3.11	-3.11
	110	0.00	3.46	-3.46	0.00	3.35	-3.35	0.00	3.09	-3.09
	111	0.07	3.57	-3.50	0.00	3.26	-3.26	0.00	3.00	-3.00
	112	0.00	3.48	-3.48	0.09	3.35	-3.26	0.00	2.92	-2.92
	113	0.00	3.38	-3.38	0.00	3.25	-3.25	0.00	2.84	-2.84
	114	0.00	3.29	-3.29	0.00	3.15	-3.15	0.00	2.76	-2.76
	115	0.00	3.20	-3.20	0.00	3.05	-3.05	0.00	2.67	-2.67
	116	0.00	3.11	-3.11	0.00	2.95	-2.95	0.00	2.59	-2.59
	117	0.00	3.01	-3.01	0.00	2.85	-2.85	0.00	2.51	-2.51
	118	0.00	2.92	-2.92	0.00	2.75	-2.75	0.00	2.42	-2.42
	119	0.00	2.83	-2.83	0.00	2.65	-2.65	0.00	2.34	-2.34
	120	0.00	2.73	-2.73	0.00	2.54	-2.54	0.00	2.26	-2.26
	121	2.47	2.64	-0.16	0.00	2.44	-2.44	0.00	2.17	-2.17
	122	0.00	2.55	-2.55	0.00	0.00	0.00	0.00	2.09	-2.09

Crop stage	Day	Nyalgunga			Nyabeda			Vihiga		
		Rainfall [mm/d]	ETc [mm/d]	Water Balance [mm/d]	Rainfall [mm/d]	ETc [mm/d]	Water Balance [mm/d]	Rainfall [mm/d]	ETc [mm/d]	Water Balance [mm/d]
late	123	0.00	2.45	-2.45	-	-	-	0.00	2.01	-2.01
	124	-	-	-	-	-	-	0.00	1.92	-1.92
	125	-	-	-	-	-	-	0.00	1.84	-1.84

Appendix 4. Manual for the Soil texture determination by the hydrometer method at the lab of CIAT-TSBF in Nairobi

Equipment
- Balance, 0.01 g readability
- Reciprocal mechanical shaker
- Hot water bath

Supplies
- Bouyoucos soil hydrometer ASTM 15H, graduated in g/L
- Measuring cylinders, 1000 mL, one per soil sample
- Plastic beakers, 400 mL, one per soil sample
- Wash bottle
- Thermometer, 0 to 110C
- Watch glasses to fit 400 mL beakers
- Stop watch
- Glass or plastic stirring rods fitted with rubber tips, one per soil sample

- Rubber stoppers to fit measuring cylinders, or plunger and rod to fit cylinders, for mixing soil suspensions.
- Volumetric flasks, 1000 mL
- Stopwatch, or clock with sweep second hand

Chemicals
- Hydrogen peroxide, 30% solution, GPR grade
- Amyl alcohol
- Sodium hexametaphosphate, technical grade

Reagents
Sodium hexametaphosphate, 10% solution: Dissolve 100 g of sodium hexametaphosphate in 1 litre of distilled water. This solution should not be stored over one month.

Procedure
- Weigh 50 ± 0.5 g of air-dry soil, sieved to pass a 2 mm sieve, into a 400 mL beaker. If soil is very sandy, use 100 g of soil. In each batch of 35 samples, include 2 standard soil samples and one blank.

- Add 125 mL of distilled water and stir the mixture to wet the soil thoroughly. Then place beakers with soil into a hot water bath at 85 to 90C.
- Add 5 mL 30% hydrogen peroxide and stir gently with a stirring rod. If necessary, add 1 or more drops of amyl alcohol to minimize foaming. Cover with a watch glass. Add further 5-mL portions of hydrogen peroxide until reaction (frothing) ceases, indicating complete destruction of organic matter. Unless soil is high in organic matter, about 20 mL total of hydrogen peroxide is usually sufficient. Heat the beakers for a short while longer, until no more bubbles appear. Ensure that the hydrogen peroxide is fully destroyed, as bubbles from residual hydrogen peroxide will cause erroneous hydrometer readings.
- Remove the beakers from the water bath and allow to cool to room temperature.
- Add 10 mL of 10% sodium hexametaphosphate solution to each sample. Allow to stand for 10 minutes.
- Transfer the samples to leak-proof bottles and shake overnight on a flat-bed or end-over-end shaker.
- Quantitatively transfer the suspension into a 1000 mL measuring cylinder, using distilled water to wash all soil particles into the cylinder. Fill to the 1000 mL mark with distilled water.
- Prepare a blank cylinder containing 10 mL of 10% sodium hexametaphosphate solution, and fill to 1000 mL with distilled water.

- Thoroughly mix the cylinders by fitting with a rubber bung and inverting the cylinder 10 times. Alternatively, the cylinders may be mixed with a circular plunger attached to a metal or wooden rod. Start the stopwatch immediately when mixing is complete.
- After mixing, quickly add 2 to 3 drops of amyl alcohol to the cylinder, and after 20 seconds place the hydrometer gently into the suspension.
- At 40 seconds, take a hydrometer reading and measure the temperature of the suspension. Also take a hydrometer reading in the blank cylinder.

- Allow the cylinders to stand undisturbed for two hours. Avoid locations which are windy or in direct sun. After two hours, take hydrometer and temperature readings in both sample and blank cylinders.

Calculations

- **Corrected hydrometer readings**

  - Corrected hydrometer reading at 40 seconds (PSH40COR):

    (PSH40SAM - PSH40BLK) + [(PST40 - 20) 0.36]

  - Corrected hydrometer reading at 2 hours (PSH2HCOR):

    (PSH2HSAM - PSH2HBLK) + [(PST2H - 20) 0.36]

  where   PSH40SAM = Hydrometer reading at 40 seconds for sample
  PSH40BLK = Hydrometer reading at 40 seconds for blank
  PST40 = Temperature at 40 seconds
  PSH2HSAM = Hydrometer reading at 2 hours for sample
  PSH2HBLK = Hydrometer reading at 2 hours for blank
  PST2H = Temperature at 2 hours

- **Percent clay (CLAY)**

  (PSH2HCOR) 100
   PSSLWT
  where   PSSLWT = Weight of air dry soil (g)

- **Percent sand (SAND)**

  100 - [(PSH40COR) 100]
                  PSSLWT

- **Percent silt (SILT)**

  100 - SAND – CLAY

Quality Control
- Two standard samples- Katumani soil and Chuka soil are used to verify the repeatability of analysis. The results should be entered into the standards sheet and should be within 10% of the median value.
- Sample repeats are carried out within each batch of 33 samples. The variation within the repeats should be less than 5%. If greater, the analysis must be repeated as it indicates that the results are not repeatable. The variation is calculated as
  Variation %=   Stdev *100
                                                    Average

Disposal practices
The soil samples should be disposed in the soil bucket for eventual disposal into the soil pit. The plastics and glassware should be allowed to stand in tap water before being washed using the lab procedure for cleaning of glassware document reference SPLAB/QP/5.1/01