Improvement of Water- and Nutrient-Use Efficiency with Optimum Agricultural Management Practices in Upland Cropping Systems in Morogoro, Tanzania

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CHAPTER 1
INTRODUCTION

1.1 Study background

Sub-Saharan Africa (SSA) is one of the poorest regions on Earth, in both agricultural environment and living standards. SSA has been struggling with low average yields of grain crops, around 1 t per hectare or less, since 1960s; it is less than half of the average yield in the world (FAO STAT, 2017). This is mainly because of the depleted unfertile soils and the unstable and uneven rainfall distribution in this region. In addition, most of the famers in SSA have insufficient economical capacity to replenish nutrients by purchasing chemical fertilizers and rely on the rainfed-agriculture system because of the lack of the irrigation system (Rockström and Falkenmark, 2015).

In semi-arid regions of SSA, crops consume less than one-third of rainfall, and 10–30% of the water runs off the surface or recharges groundwater (Rockström and Falkenmark, 2015). The loss of fertile surface soil caused by water erosion directly results in productivity losses as high as 2–3% annually (Lal, 1995; World Bank, 2008). Furthermore, it is reported that nutrient leaching loss caused by severe rainfall events accounts for a large part of nutrient pool in soils in semiarid tropical Africa (Chikowo et al., 2004, Nyamangara et al., 2003). With these conditions, it is essential to minimize the losses of water and nutrient from the cropping system and to increase the water- and nutrient-use efficiency for the improvement of the agricultural production in SSA (Tilman et al., 2002).

Tanzania has a wide range of soil types, which have developed from many types of geological parent materials under a variety of time scales and environmental conditions as affected by the Great Rift Valley (Jones et al., 2013). Morogoro is one of the regions where a range of soil types can be observed in a limited space in relation to a range of climatic conditions due to the presence of the Uluguru Mountains. There are strongly weathered clayey soils, such as Ferralsol and Acrisol, which are rich in iron and aluminum oxides and have low cation exchange capacity (CEC), and sandy soils, such as Fuluvisol and Arenosol, which also have low CEC because of their low clay content. These soil types greatly differ in soil texture, and consequently in organic matter content, water and nutrient retention capacity and the ability to mineralize carbon (C) and nitrogen (N) (Iqbal et al., 2015). In addition, annual precipitation in Morogoro ranges from 500 mm to over 1500 mm basically along the slope direction and the elevation of the mountains, and the rainy season is usually bimodal and have unstable distribution of rainfall pattern. These variations in soil and climate conditions result in the diversified crop managements on/around the Uluguru Mountains in Morogoro (Yamane and Higuchi, 2005). Various vegetables cultivation can be found in middle to high elevation dominated by precipitation and temperature along the elevation, for instance tomato, cabbage, pepper, and indigenous vegetables. Because of the easy access to Dar es Salaam, a lot of cash crops are cultivated for the market on the Uluguru Mountains. Besides expanding the intensive agricultural production in Morogoro region, the sustainability of the cropping systems has been concerned with rapid population growth and increasing land use pressure (Ahn, 1977; De Putter et al., 2007).

Water erosion is a crucial trigger of land degradation problems due to the human activities in tropical agroecosystems (Gabarrón-Galeote et al., 2013; Lal, 2001). The accelerated soil water erosion in Tanzania, including in the Uluguru Mountains in Morogoro, has also been reported by many researchers since 1970s (e.g., Rapp, 1975; Ahn, 1977; Kaihura et al., 1999; Mwango et al., 2016), and still it is a special concern of land degradation in the upland cropping systems. The spatial-temporal heterogeneity of environmental conditions, i.e. soil and rainfall, result in a variety of water erosion characteristics and make it difficult to control water erosion on crop lands (Buendia et al., 2016; Cerdà, 2002). Water erosion models, such as Universal Soil Loss Equation (USLE) and Water Erosion Prediction Project (WEPP) model, are generally used for estimating the amount of soil loss in slopes or watersheds. However, these models cannot give us the generation process of water erosion associated with surface runoff water and soil loss. Surface runoff, which is a principal trigger of water erosion, is controlled by the rainfall intensity which substantially fluctuates during a rainfall event and the infiltration rate which is regulated by surface soil moisture condition and soil physical property. Therefore, the evaluation of water balance including rainfall, surface runoff and soil water content within a rainfall event is effective to reveal the mechanism and the influential factors of the surface runoff generation and infiltration process in the field. An improved knowledge of water erosion characteristics in relation to their mechanism and influential factors, which may greatly change with the environmental conditions, will inform better management to improve agricultural production through reducing the losses of water and soil by water erosion in Morogoro.

The optimum land managements in terms of suppressing water erosion are varied with soil types with a high spatial variability in tropical areas. Drainage capacity and moisture retention capacity of soils which control runoff generation and soil loss through water erosion are influenced by soil physical properties, such as soil texture, soil structure and clay mineralogy of soils (Greene and Hairsine, 2004; Reichert et al., 2009). In addition, the tolerance of soils to the detachment by rainfall or surface runoff water is dependent on these soil physical properties and organic matter content. For example, typical sandy soils consist mostly of quartz with high weathering resistance and have little soil organic matter and no pedogenic horizons. Although such sandy soils have relatively high permeability resulting in high leaching potential and low runoff coefficient, they are generally prone to be lost by water erosion owing to its weak structure. Therefore, the soil properties varying along the soil types should be evaluated when the conservation land management is established based on the generation mechanism of water erosion.

The significance of application of organic materials into cropland has been pronounced not only with protecting surface soils against water erosion in sloping cropland but also with increasing soil organic matter and improving water and nutrient use efficiency (Palm et al., 2001; Prosdocimi et al., 2016). However, it has not been thoroughly understood what kind of organic matter management can enhance water and nutrient dynamics under a certain environmental condition especially in tropical agroecosystems. Soil water and N dynamics and the decomposition of organic matter are generally controlled by soil texture, which regulates the water- and nutrient-holding capacities and the microbial activities in soils (Sugihara et al., 2010b; Sugihara et al., 2012b; Vanveen and Kuikman, 1990). Sugihara et al. (2010b) reported that the rapid turnover of soil microbes in a sandy soil compared with a clayey soil in a maize cropland in Tanzania resulted in an increased nutrient supply in sandy soils. However, there are still a limited number of studies which evaluated the effect of soil types on soil N dynamics with field experiments in semi-arid to sub-humid tropical Africa.

In addition, the quality and application method of organic materials regulates the N release patterns. It is generally said that the decomposition rate of organic matter depends on its N content, carbon (C) to N ratio, and lignin and polyphenol content (Nicolardot et al., 2001; Palm et al., 2001; Baijukya et al., 2006). Further, the application methods used with crop residues (i.e., incorporation or mulching) will also affect the water regime around residues and surface soil (Zeleke et al., 2004; Dahiya et al., 2007) and the contact area of residues with soil, and therefore could subsequently influence the decomposition and nutrient release rates of the crop residues (Schomberg et al., 1994; Stemmer et al., 1999). Generally, the decomposition rate of mulched residues is lower than that of incorporated residues because they have smaller area of attachment to the soil and are subjected to alternating wet and dry periods that may restrict microbial activity (Coppens et al., 2006). However, mulching can suppress evaporation and remain soil moisture condition high especially in the top layer compared with incorporation (Dahiya et al., 2007), which can mitigate the decreases of microbial activity in the surface soil and the rate of organic matter decomposition through drying surface soil due to a high evaporation rate in the tropics. Therefore, the decomposition and nutrient release processes of mulched residues are strongly associated with soil moisture dynamics along with rainfall patterns under natural condition. Hence, it is critical to understand the soil water and N dynamics associated with the decomposition process of applied residues and the N uptake by crops based on field experiments to develop the suitable crop residue managements for the upland cropping systems under various environmental conditions in Morogoro.

1.2 Study objectives

The final goal of this study was to investigate the optimum agricultural management to improve the water- and nutrient-use efficiency in the upland cropping systems in Morogoro, Tanzania, with special reference to its diversified soil types and climatic conditions. Toward the final goal, field experiments were carried out in the representative sites in Morogoro, aiming (1) to evaluate water erosion characteristics based on short-term water budget in sloping croplands under different environmental conditions in the Uluguru Mountains, and (2) to evaluate water, carbon and nitrogen dynamics under different agricultural practices using crop residues in maize croplands with contrasting soil textures.

The thesis comprises the following chapters: In Chapter 2, the geological and climatic conditions and the soils of the studied sites in Morogoro, Tanzania, are described. In Chapter 3, surface runoff generation and soil loss under different soil and rainfall properties in the Uluguru Mountains are discussed. In Chapter 4 and Chapter 5, soil carbon and nitrogen dynamics under different crop residue managements at maize croplands with contrasting soil textures are discussed. In Chapter 6, a general discussion is presented and main conclusions are summarized.

CHAPTER 2
GENERAL DESCRIPTION OF THE STUDY SITES

2.1 General characteristics of the study sites

Four sites were selected based on the soil texture, slope, and rainfall in or around the Uluguru Mountains in Morogoro, Tanzania, designated NY, TA, SO and MA. NY site is at the highest elevation (1,600 m above sea level) on the west side of the Uluguru Mountains. This location has the lowest temperature and highest rainfall amount, and is therefore dominated by the cultivation of various cash crops such as tomato (*Solanum* l*ycopersicum* L.), cauliflower (*Brassica oleracea* var. *botrytis*) and cabbage (*Brassica oleracea* var. *capitata*). Soil texture of the top layer is silty clay with 47% clay. TA site is at the lowest elevation, 450 m above sea level, on the east side of the mountains. It has the highest temperatures and rainfall, 1,600 mm annually. Pineapples (*Ananas comosus*), bananas (*Musa spp.*), coconuts (*Cocos nucifera* L.) and spices (*Piper nigrum*) are mainly cultivated in this region. Soil texture of the top layer is clay, with 46% clay. SO and MA sites are in experimental fields of the Sokoine University of Agriculture, at the foot of the Uluguru Mountains, and MA site is 7 km northwest of SO site (Fig. 2.1). The main cultivated plants are maize (*Zea mays* L.) and sisal (*Agave sisalana*). Soil texture of the top layer is sandy clay loam containing 59% sand and 28% clay at SO, and sand containing 92% sand and 3% clay at MA.

The Uluguru Mountains lie 200 km inland from the Indian Ocean and form part of a chain of mountains in East Africa collectively called the Eastern Arc Mountains (Burgess et al., 2007). The elevation ranges from around 300 m at lowest point and to about 2,600 m at highest point. The eastern slope of the mountains has higher precipitation brought by the clouds from the

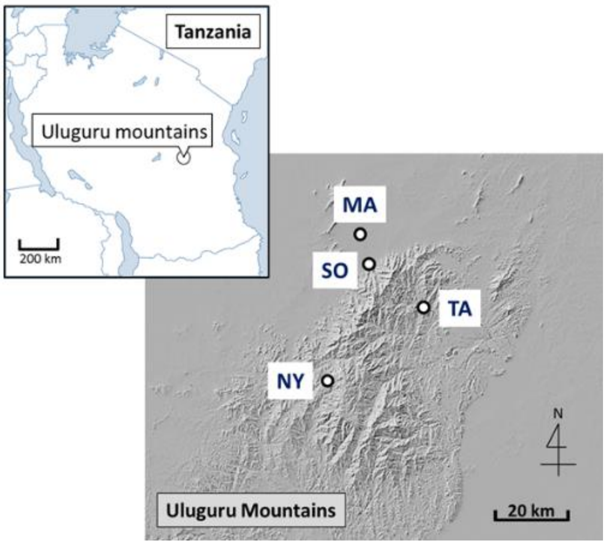

Figure 2.1 Map showing the location of the four experimental sites in the Uluguru Mountains in Morogoro, Tanzania

Table. 2.1 Site description and soil physicochemical properties of surface layer (0–15 cm depth) at the four experimental sites

Site	Altitude (m)	Average temperature※1 (℃)	Total Rainfall ammount※1 (mm)	Soil classification※2	Clay (%)	Silt (%)	Sand (%)	pH	EC ($\mu S\ cm^{-1}$)	CEC ($cmol_c\ kg^{-1}$)	CEC/Clay ($cmol_c\ kg^{-1}$)	Total C ($g\ kg^{-1}$)	Total N ($g\ kg^{-1}$)
NY	1600	18.2	980	Aquertic Haplustalfs	47	41	12	5.6	42.2	15.4	33	28.3	2.5
TA	450	25.4	1625	Typic Haplustepts	46	12	42	5.8	27.0	12.1	26	34.5	2.1
SO	550	25.4	538	Kanhaplic Haplustalfs	28	13	59	5.9	37.5	9.9	36	13.0	1.1
MA	500	25.0	528	Ustic Quartzipsamments	3	5	92	5.0	12.1	1.4	54	3.3	0.3

※1 The value during observation period.
※2 Based on Soil Survey Staff (2014)

Indian Ocean. The site description was shown in Table 2.1. The rainy season is usually bimodal in the region. The long rainy season (February through May) has a greater amount of precipitation and the precipitation is more evenly distributed than in the short rainy season (October through December) when the duration and intensity of precipitation is less predictable. According to the rainfall probability map in Tanzania, the mean annual rainfall is 1000─1250, 1500─1750, 750─1000, and 500─750 mm in NY, TA, SO, and MA, respectively. Thus, the amount of rainfall in the year of the erosion experiment in 2010─2011 was comparable with that in a normal year, while that in the years of the cultivation experiment in 2012─2014 was less than that in a normal year.

2.2 Description of the experimental plot

2.2.1 Erosion plots

Erosion plots were installed in all the four sites, NY, TA, SO, and MA. The sites were first cleared of natural vegetation (mainly consisting of shrub and grass) and extracted their roots using hoe and knife, and then the erosion plots were enclosed by corrugated iron sheets. These erosion plots were kept free of weeds by hands throughout the experimental period. Two erosion plots were established for each site (Fig. 2.2). The plot size was width 0.8 m × slope length 2.4

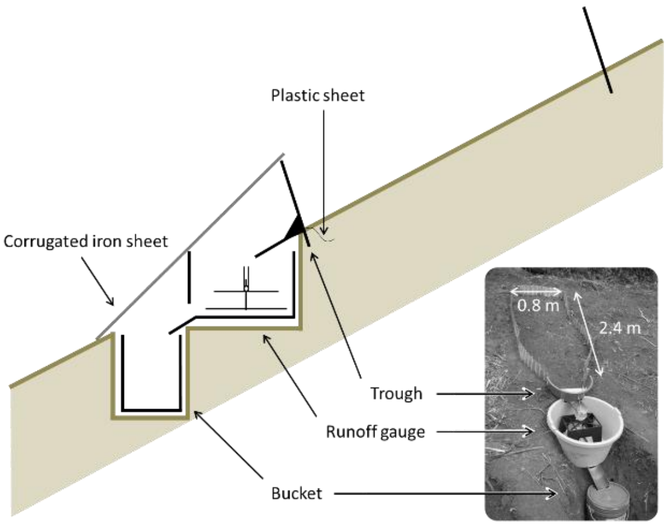

Figure 2.2 Schematic diagram of runoff gauge and bucket at end of a runoff plot.

m, which were made small enough to exclude the micro-topography on the slope influencing runoff dynamics and to clarify the water balance and the timing of runoff occurrence within the plot. The runoff gauges had the tipping bucket system and were connected to a data logger (CR1000; Campbell Scientific, Inc., Logan, UT, USA) to record cumulative runoff amount every 10 minutes, which is the same design as that of Funakawa et al. (2007).

2.2.2 Cultivation experiment in Tanzania

Cultivation experiment was conducted at the clayey (SO) and sandy (MA) sites. The experimental design included the following five treatments:

(1) Ctrl plot: control (no residue input);

(2) F plot: chemical fertilizer-treated plot (urea equivalent to 40 kg N ha^{-1});

(3) M-In plot: maize residue-incorporated into soil in the plot (5.0 Mg ha^{-1} on a dry basis of maize straw and leaf equivalent to 2.4 Mg C ha^{-1} and 40 kg N ha^{-1}; C:N ratio = 60);

(4) M-On plot: maize residue-mulching in plot (same amount as the M-In plot);

(5) P-In plot: cowpea residue incorporation into the soil in the plot (2.7 Mg ha^{-1} on a dry basis of cowpea straw and leaf equivalent to 0.8 Mg C ha^{-1} and 40 kg N ha^{-1}; C:N ratio = 21).

Entire experimental fields at both the clayey and sandy sites were cleared prior to the experiment in November 2011. After the original vegetation was slashed, the aboveground biomass, but not root biomass, was removed from the field. Cowpea (*Vigna unguiculata* (L.) Walp.) and maize (*Zea mays* L. *'Stah'*) were used as the applied residues in the current study. These two species have contrasting qualities in terms of C:N ratio and are readily available to local farmers in Tanzania. Both cowpea and maize were cultivated on a cropland adjacent to the experimental field at the clayey site during the short rainy season, December to February in both years. Crops were harvested several days before the initiation of cultivation in the experimental field, and moisture content was measured to calculate the biomass, and they were brought to the experimental field at both the clayey and sandy sites. In the crop residue-incorporated plots, i.e., M-In and P-In plots, the respective crop residues (leaf and stem) were chopped into 15–20 cm pieces on each plot, and then evenly distributed on the soil surface and incorporated into the soil (0–15 cm depth) with hand hoes (incorporation). For the M-On plot, the chopped residues were placed on the soil surface after the cultivation of fields (mulching). In the Ctrl and F plots, cultivation was conducted using hand hoes on the same day that crop residues were applied. The crop residues were applied after the first heavy rainfall event in March in both 2012 and 2013, when Tanzanian farmers generally begin to sow their crops. To avoid severe N depletion after excessive C input, seeding was conducted at least 1 week after crop residue application and immediately after a rainfall event (Sugihara et al., 2012a). All treatment plots, including the Ctrl plot, received triple superphosphate equivalent to 20 kg P ha^{-1} as a basal fertilizer following the fertilizer recommendation from the Ministry of Agriculture, Food Security and Co-operatives in Tanzania. The chemical fertilizers, urea and triple superphosphate, were broadcast immediately after seeding on the same day.

Each 8 × 8 m treatment plot had three replications, which were laid out in a randomized block design; an unplanted > 1 m wide strip separated each plot. Two seeds of maize (Zea mays L. '*Stah'* and '*TMV-I*' in the clayey and sandy sites, respectively) were planted per hole at a spacing of 30 × 80 cm on 13 and 14 March 2012 at the sandy and clayey sites, respectively, and on 12 and 14 March 2013 at the sandy and clayey sites, respectively (i.e., 0 days after planting (DAP)). Seedlings were thinned to one plant per hole at 14 DAP. All treatment plots were weeded at around 30 DAP with hand hoes, and all weeded materials were removed from the plots. The maize was harvested on 26 (105 DAP) and 28 June 2012 (106 DAP) at the sandy and clayey sites, respectively, and on 20 (100 DAP) and 22 June 2013 (100 DAP) at the clayey and sandy sites, respectively. After harvest in 2012, the aboveground biomass of maize, but not root biomass, was removed from the field. When preparing for seeding, we also removed all short-grass biomass, which grew during the dry and short rainy season, from all treatment plots. Because a severe drought had been forecasted by the Tanzanian Meteorological Agency ahead of the rainy season in 2013, irrigation was conducted during the growing period in 2013 at both the clayey and sandy sites. Water equivalent to 10 mm of rainfall was applied to each plot with a hose, and irrigation was conducted every week from April to June 2013, a total of eight times (10 mm per irrigation for a total of 80 mm). Sampling of gases, plants and soils were conducted immediately before each irrigation session to minimize the disturbance of soil moisture content and mineralization of SOM.

CHAPTER 3
SURFACE RUNOFF GENERATION AND SOIL LOSS UNDER DIFFERENT SOIL AND RAINFALL PROPERTIES IN THE ULUGURU MOUNTAINS, MOROGORO

3.1 General

Water erosion is a main concern driving land degradation in sloping croplands in SSA. Soil and rainfall properties greatly differ with location, resulting in various water erosion characteristics (Cerdà, 1998a; Cerdà, 2002; Buendia et al., 2015). For example, in the Uluguru Mountains where the current study was conducted in Tanzania, there are areas mostly covered by strongly weathered clayey soils and by alluvial coarse textured soils around the foot of these mountains. Precipitation also varies with slope orientation and elevation, which ranges from 400 to 2,630 m. The eastern side of the mountains is one of the rainiest areas in Tanzania and receives more than 2,000 mm of annual precipitation, compared with 400–500 mm in the lowlands on the west side (Moore, 1979). To establish management practices for preventing water erosion, it is necessary to evaluate the water erosion risk and investigate influential factors of water erosion characteristics at each location with various soil and rainfall properties.

Water erosion is controlled by two factors: the amount of surface runoff and the sediment concentration in that water (Kinnell and Risse, 1998; Chaplot and Le Bissonnais, 2003). Generally, surface runoff is believed to occur when rainfall intensity exceeds the infiltration rate on slopes, so its ratio with rainfall amount (runoff ratio) is regulated by the correlation between infiltration rate and rainfall intensity (Calvo-Cases et al., 2003). Infiltration rate plays an important role as it controls water erosion with spatial and temporal variability at pedon (Cerdà, 1997; Cerdà, 1999) and watershed scales (Keesstra, 2007; Keesstra et al., 2009). Infiltration rate depends on various influences, such as air entrapment in soil (Wang et al., 1998), hydraulic conductivity (K) of the surface soil, which is regulated by soil texture and structure (Saxton et al., 1986; Mamedov et al., 2001), and vegetation (Cerdà, 1998b) or residue (Cerdà et al., 2016) cover. Additionally, infiltration rate varies with soil moisture conditions at the beginning of a rainfall event (Le Bissonnais and Singer, 1992; Le Bissonnais et al., 1995). Le Bissonnais et al. (1995) observed that runoff ratios were between 30% and 70% for initially air-dried plots, whereas they were between 70% and 90% for field-moist plots. It is generally said that infiltration rate fluctuates according to the aforementioned factors during rainfall events. Nevertheless, it is unclear how the specific rainfall characteristic in SSA such as short (i.e. half a day or less), high rainfall intensity and substantial fluctuation (Moore, 1979; Wainwright and Parsons, 2002; Salako,

2006) interact for runoff generation within rainfall events. Therefore, water balance was measured during every rainfall event, i.e. rainfall amount, soil water content, and runoff amount at 10-minute intervals overcoming the technical difficulties of continuously measuring these components in the field, to reveal how they affect surface runoff generation.

Sediment concentration tends to increase when the initial soil moisture condition at the beginning of a rainfall event is dry, because slaking of soil aggregates increases with initially dry soil (Le Bissonnais et al., 1995; Defersha and Melesse, 2012). Defersha and Melesse (2012) reported that sediment concentration from an initially air-dry surface was 1.4 times higher than from an initially wet surface in a laboratory experiment. However, in the field, the initial soil moisture condition at the beginning of a rainfall event is controlled by the rainfall pattern plus the water retention capacity and hydraulic conductivity of the soil, which are affected by soil texture and structure at various locations (Saxton et al., 1986; Wildemeersch et al., 2015). Le Bissonnais et al. (1995) showed that soils with high clay content had the lowest erosion rate when they were rewetted, whereas soils with high organic carbon content had the lowest erosion rate in air-dry conditions. Rainfall intensity (Wischmeier and Smith, 1978; Kinnell and Risse, 1998) also influences soil erodibility. These previous studies emphasize the complexity of the effect of initial moisture content, and the interactions between soil properties and climate (Le Bissonnais et al., 1995), so that it is necessary to verify the interaction of these influences with field experiments.

Therefore, the objective of this study was to evaluate water erosion characteristics and water erosion risks, and to clarify the factors affecting runoff and soil loss based on the analysis of rainfall events at four sites with varying soil and rainfall properties using small erosion plots in the Uluguru Mountains, Tanzania.

3.2 Material and methods

3.2.1 Site descriptions in four experimental sites

The field erosion experiment was conducted at four sites in the Uluguru Mountains in Tanzania (NY, TA, SO, and MA) during one rainy season, from November 2010 through May 2011 (160 days). These mountains have faced accelerating water erosion caused by land-use change since the early twentieth century (Ahn, 1977). Two erosion plots were installed for each site. The general description of the study area was written in the section 2.1.1 in Chapter 2, and the description of the erosion plots was shown in the section 2.2.1.

The NY site is at the highest elevation (1,600 m above sea level) on the west side of the Uluguru Mountains. This location has the lowest temperature and highest rainfall amount, and is therefore dominated by the cultivation of various cash crops such as tomato (*Solanum lycopersicum* L.), cauliflower (*Brassica oleracea* var. *botrytis*) and cabbage (*Brassica oleracea* var. *capitata*). Soil texture of the top layer is silty clay with 47% clay. The TA site is at the lowest elevation, 450 m above sea level, on the east side of the mountains. It has the highest temperatures and rainfall, 1,600 mm annually. Pineapples (*Ananas comosus*), bananas (*Musa spp.*), coconuts (*Cocos nucifera* L.), and spices (*Piper nigrum*) are mainly cultivated in this region. Soil texture of the top layer is clay, with 46% clay. The SO and MA sites are in experimental fields of the Sokoine University of Agriculture, at the foot of the Uluguru Mountains. The MA site is 7 km northwest of SO. The main cultivated plants are maize (*Zea mays* L.) and sisal (*Agave sisalana*). Soil texture of the top layer is sandy clay loam containing 59% sand and 28% clay at SO, and sand containing 92% sand and 3% clay at MA. The soil depths at all sites were confirmed to be more than 1 m by making a soil pit at each site. Based on field observation, soil crust is easily formed at both NY and SO, which likely inhibits the infiltration of water, and none of the sites had surface stone cover. More detailed soil physicochemical properties are shown in Table 2.1.

3.2.2 Environmental factors

During the experimental period at each site, volumetric water content (VWC) of soils at depths 0–15, 15–30 and 30–60 cm were continuously measured with time domain reflectometer probes (CS616 Water Content Reflectometer; Campbell Scientific, Inc.) with no replication. Rainfall amount was also measured with a tipping bucket rain gauge at every site. Data including surface runoff water, soil moisture and rainfall were recorded by CR10X data loggers at 10-minute intervals.

3.2.3 Rainfall event and runoff amount analysis

A rainfall event was defined as precipitation with total rainfall > 5 mm and a rain-free period of no more than 10 hours (Miyata et al., 2009). Information about each rainfall event, such as date, duration, total rainfall amount and maximum rainfall intensity was recorded (see Appendix I). The rainy season was divided into two periods to evaluate the seasonal variation of erodibility; the first half from November through February, which corresponds to a small rainy season, and the second half from March through May, which corresponds to a big rainy season.

3.2.4 Soil physical properties and sediment soil analysis

Undisturbed soil core samples were collected from soil profiles at all sites at depths of 0–5, 5–10, 20–25 and 40–45 cm with three replications, respectively, using a 100 cm^3 (5-cm height) core sampler. All core samples were used for measuring bulk density (Grossman and Reinsch, 2002) and saturated hydraulic conductivity via constant-head and falling-head methods (Klute, 1965) and, except for cores from 0–5 cm depth, the soil moisture characteristic curve using a soil column for 0 (saturated) to −3.1 kPa and pressure plate for −9.8 to −98.0 kPa (Dane and Hopmans, 2002). Sediment and soils trapped in buckets were collected at intervals of about two weeks, then air-dried and weighed.

3.2.5 Data analysis

Sediment concentration in the surface runoff water between two adjacent collection dates (periodic sediment concentration) was calculated from total sediment amount collected in the bucket and total runoff amount measured by runoff gauges over the period. Periodic sediment concentration was multiplied by daily runoff amount to calculate daily soil loss during the period.

To investigate the effect of the antecedent soil moisture condition on subsequent surface runoff generation during each rainfall event, those events were classified into three groups according to the initial VWC at 0–15 cm depth at the beginning of each event: wet condition is more than field capacity (matric potential $\Phi_m = -3.6$ kPa); dry condition is less than depletion of moisture content for normal growth ($\Phi_m = -98.1$ kPa); and moist condition is between those two water constants. These criteria were set considering soil moisture mobility. Multiple regression models were constructed to determine how well the observed runoff amount in rainfall events could be explained by selected independent variables (Prats et al., 2012). This was done using a stepwise forward selection procedure, in which the independent variables were selected in order of their significant contribution ($p < 0.05$) to the explained variance. The independent variables were rainfall amount, maximum I_{10}, initial VWC and duration. The rainfall had to be transformed by taking the logarithm for Shapiro-Wilk test not to reject normality. Statistical correlation was also tested between soil loss and environmental parameters (rainfall amount and average and maximum I_{10}) in each sampling period, and between sediment concentration and environmental parameters in each sampling period (González-Pelayo et al., 2010). All statistical analyses were performed with SigmaPlot 11.0 (Systat Software, Inc.).

3.3 Results

3.3.1 Soil physical properties

Bulk density at the two mountainous sites NY and TA ranged from 1.0 to 1.1 Mg m^{-3}, which was significantly lower than that at the two foothill sites SO and MA (1.4 to 1.6 Mg m^{-3}, Table 3.1). Bulk density generally decreased with soil depth at all sites. Saturated hydraulic conductivity (K_s) of the surface soil (0–5 cm depth) was in the order TA > MA > SO > NY, and it was clearly lower than that of the sub-surface soil (5–10 cm depth) at all sites (Table 3.1). The volume of large size pores was highest at TA and MA, where K_s was relatively high (Table 3.1).

Table 3.1 Bulk density, saturated hydraulic conductivity and soil water constants at different depths at four sites.

Site	Depth	Bulk density		Saturated hydraulic conductivity (K_s)		Volumetric water content at saturated point		Field capacity※1		Depletion of moisture content for normal growth※2		Volume of large size pores※3
	(cm)	($Mg\ m^{-3}$)		($mm\ h^{-1}$)		($m^3\ m^{-3}$)		($m^3\ m^{-3}$)		($m^3\ m^{-3}$)		($m^3\ m^{-3}$)
NY	0-5	1.0	(0.02)	15.1	(13.0)							
	5-10	1.0	(0.02)	88.9	(1.44)	0.56	(0.00)	0.46	(0.00)	0.40	(0.00)	0.16
	20-25	1.1	(0.01)	1.02×10^2	(46.8)	0.51	(0.01)	0.49	(0.01)	0.44	(0.01)	0.07
	40-45	1.0	(0.02)	53.5	(10.1)	0.51	(0.00)	0.47	(0.01)	0.42	(0.01)	0.09
TA	0-5	1.0	(0.05)	4.50×10^2	(1.26×10^2)							
	5-10	1.0	(0.03)	3.66×10^4	(9.72×10^3)	0.59	(0.01)	0.40	(0.01)	0.31	(0.01)	0.28
	20-25	1.1	(0.02)	3.74×10^2	(61.2)	0.55	(0.01)	0.42	(0.01)	0.33	(0.01)	0.23
	40-45	1.1	(0.03)	1.89×10^2	(57.6)	0.53	(0.01)	0.45	(0.01)	0.33	(0.01)	0.20
SO	0-5	1.4	(0.02)	99.8	(46.8)							
	5-10	1.4	(0.03)	1.56×10^4	(1.26×10^4)	0.46	(0.01)	0.34	(0.01)	0.23	(0.01)	0.23
	20-25	1.4	(0.02)	84.8	(46.8)	0.40	(0.01)	0.33	(0.00)	0.26	(0.00)	0.15
	40-45	1.5	(0.02)	55.6	(6.48)	0.41	(0.01)	0.36	(0.01)	0.26	(0.01)	0.14
MA	0-5	1.4	(0.02)	2.72×10^2	(39.6)							
	5-10	1.5	(0.02)	1.86×10^2	(1.76)	0.34	(0.00)	0.24	(0.00)	0.04	(0.00)	0.30
	20-25	1.6	(0.02)	78.0	(7.92)	0.31	(0.01)	0.22	(0.01)	0.06	(0.00)	0.25
	40-45	1.6	(0.02)	65.7	(14.4)	0.30	(0.00)	0.23	(0.01)	0.06	(0.00)	0.24

The values given in parentheses are standard error (N = 5 for 0-5 cm depth and N = 3 for others).
※1 VWC at −3.1 kPa of matric potential.
※2 VWC at −98.0 kPa of matric potential.
※3 The difference of VWC between saturated point and depletion of moisture content for normal growth.

Table 3.2 Total rainfall, runoff, soil loss, runoff ratio and sediment concentration in surface runoff water during the experimental period.

Site	Number of rainfall events	Total rainfall	Total runoff		Total soil loss		Total runoff ratio	Total sediment concentration
		(mm)	(mm)		($Mg\ ha^{-1}$)		(%)	($g\ L^{-1}$)
		A	B		C		100*B/A	100*C/B
NY	43	980	157.2	(2.1)	36.1	(5.2)	16.0	23.0
TA	43	1625	180.5	(10.2)	47.3	(5.3)	11.1	26.2
SO	23	538	89.5	(9.8)	15.9	(2.5)	16.6	17.8
MA	25	528	62.7		22.8		11.9	36.4

The values given in parentheses are standard deviation.
MA had no replicate because of plot No. 2 had mechinery trouble.

3.3.2 Temporal variation of rainfall and soil moisture at the four sites

Total rainfall during the experimental period was 980, 1625, 538 and 528 mm at NY, TA, SO and MA, respectively, and the corresponding number of rainfall events was 43, 43, 23 and 25 (Table 3.2). Information on each rainfall event is shown in Appendix. Daily rainfall and VWC are shown in Fig. 3.1. The rainfall amount was smaller in the first half (November–February), corresponding to a small rainy season, than the second half (March–May), corresponding to a big rainy season at all sites.

At the NY site, the surface layer was gradually saturated with water from 1 February, the beginning of the rainy season. Subsequently, the entire layer from the 0 to 60-cm depth was

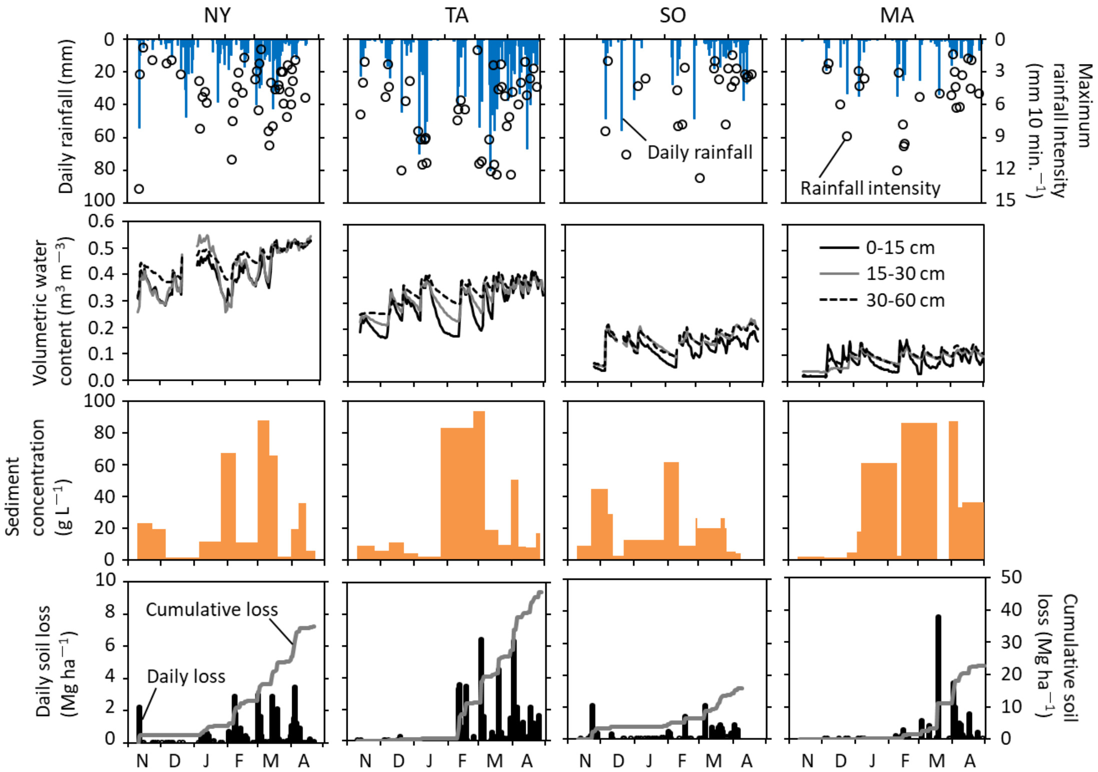

Figure 3.1 Daily rainfall, maximum rainfall intensity, daily volumetric water content, periodic sediment concentration, and daily and cumulative soil loss at four sites over the experimental period.

Table 3.3 Rainfall characteristic and slope degree at four sites.

Site	Total Rainfall ammount※1 (mm)	I_{10}※2 Average	Maximum	Slope gradient (degree)
NY	980	4.7	13.7	20
TA	1625	6.5	12.4	20
SO	538	4.8	12.7	5
MA	528	5.0	12.0	5

※1 Mean value during observation period from November 2010 to May 2011.
※2 The highest volume of precipitation occurring in 10 minutes, in mm 10 min.$^{-1}$, within the all rainfall events.

saturated by mid-March (Fig. 3.1). This is because rainfall at this site was intermittent and non-torrential, and the average I_{10} of all rainfall events through the experimental period, 4.7 mm 10 min^{-1}, was lowest among the four sites (Table 3.3). In addition, there is a clay-rich layer below 60 cm depth, which has > 70% clay, and it suppressed the permeation of water to deeper layers. The TA site received the largest amount of rainfall and the average I_{10} through the experimental

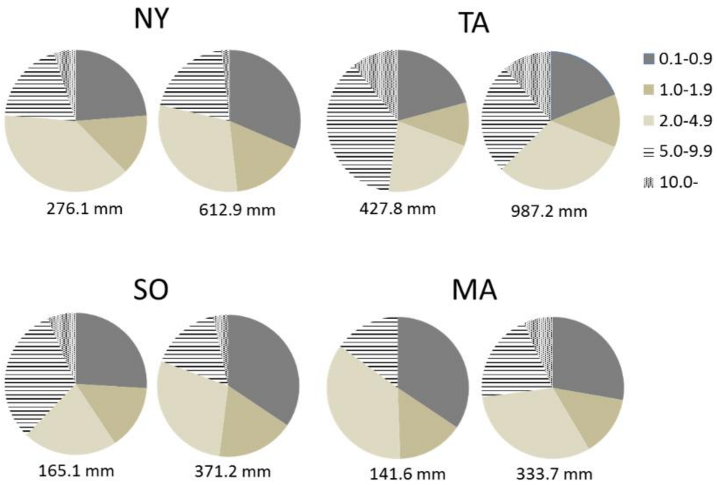

Figure 3.2 Proportion of the amount of rainfall with different rainfall intensities (mm 10 min^{-1}) from November to February (left) and from March to May (right). The numbers below graphs show the total rainfall amount of each period.

period was the highest of the four sites (Table 3.3). Because of high K_s in the surface and sub-surface layers, soil water in the surface layer was displaced immediately after rainfall events, so this layer became dry during a short dry spell prior to the big rainy season in early February. The maximum I_{10} through the experimental period was 12.4 mm 10 min^{-1}.

The SO site had little total rainfall compared with the mountainous sites, and the average I_{10} through the whole rainy season was the smallest of the four plots (Table 3.3). Average I_{10} was 5.8 mm 10 min^{-1} in the first of the rainy season (November–February), and it decreased to 4.1 mm 10 min^{-1} in the later rainy season (March–May). VWC at the 30–60 cm depth increased little over the experimental period.

The MA site had nearly the same total rainfall and I_{10} as SO, and the average I_{10} decreased from 6.1 mm 10 min^{-1} in the first half to 4.1 mm 10 min^{-1} in the second half of the rainy season. VWC at MA was generally low at all depths because of the lower holding capacity of the sandy soil, and it decreased immediately after rainfall events.

The maximum rainfall intensities recorded during the experimental period were 13.7, 12.4, 12.7 and 12.0 mm per 10 minutes at NY, TA, SO and MA, respectively, whereas K_s of the surface layer was respectively 2.5, 72.0, 16.8 and 45.6 mm per 10 minutes. Rainfall intensity exceeding K_s of the surface layer was observed only at NY, where K_s was the lowest of the four sites.

The rainfall amount was smaller in the first half (November–February) than the second half (March–May, Fig. 3.2). High portion of heavy rainfall (> 5.0 mm per 10 min) was observed at TA through the experimental period and at SO in the early half of the rainy season (Fig. 3.2).

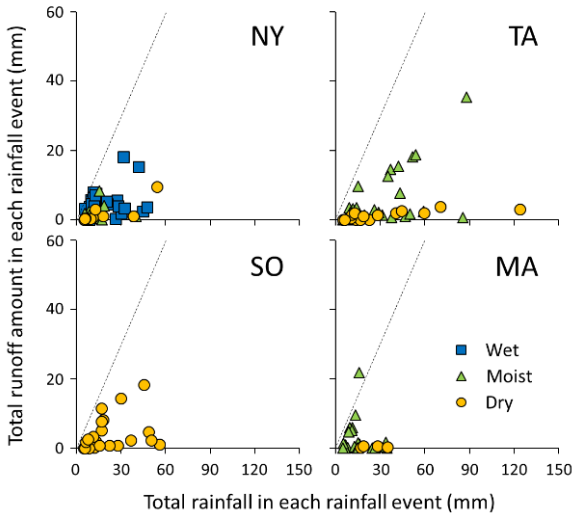

Figure 3.3 Relationship between total precipitation and total runoff within each rainfall event. Dotted line shows 1:1 ratio. N = 86, 86, 46 and 25 in NY, TA, SO, and MA, respectively. Every rainfall events were classified according to the initial VWC of 0—15 cm depth at the beginning of each event; Wet is more than field capacity (matric potential Φ_m= −3.6 kPa), Dry is less than depletion of moisture content for normal growth (Φ_m=−98.1 kPa), and Moist is between the two water constants.

3.3.3 Temporal variation of surface runoff at the four sites

Surface runoff usually occurred immediately after the beginning of rainfall events at all sites except some events with small intensity. Total runoff amount and its ratio to total precipitation (runoff ratio) during the experimental period are shown in Table 3.2. The amount of total surface runoff in descending order was TA, NY, SO and MA, and total runoff ratio was largest at SO followed by NY, MA and TA.

Figure 3.3 shows the relationship between total precipitation and total runoff within each rainfall event. The events were classified by three conditions, dry, moist and wet, according to initial water content of the surface soil. The wet condition was observed only at NY. When the antecedent soil moisture condition was dry, the runoff generation was lower compared to that of the moist or wet conditions. Average runoff ratio during rainfall events was 7.4, 15.9 and 32.9 of dry, moist and wet, respectively, in NY; 4.3 and 17.8 of dry and moist, respectively, in TA; 19.0 of dry in SO; and 7.3 and 23.4 of dry and moist, respectively, in MA.

Figure 3.4 shows an example of fluctuation in rainfall, surface runoff and VWC, and water balance of rainfall events with various antecedent soil moisture conditions. When the surface soil was dry at the beginning of a rainfall event with low VWC (0.28 m^3 m^{-3}) (Fig. 3.4a), the high water holding capacity of the top layer (see Table 3.1) led to a high infiltration rate and hence reduced runoff ratio (2.6%). Conversely, when the soil was initially wet, the surface layer

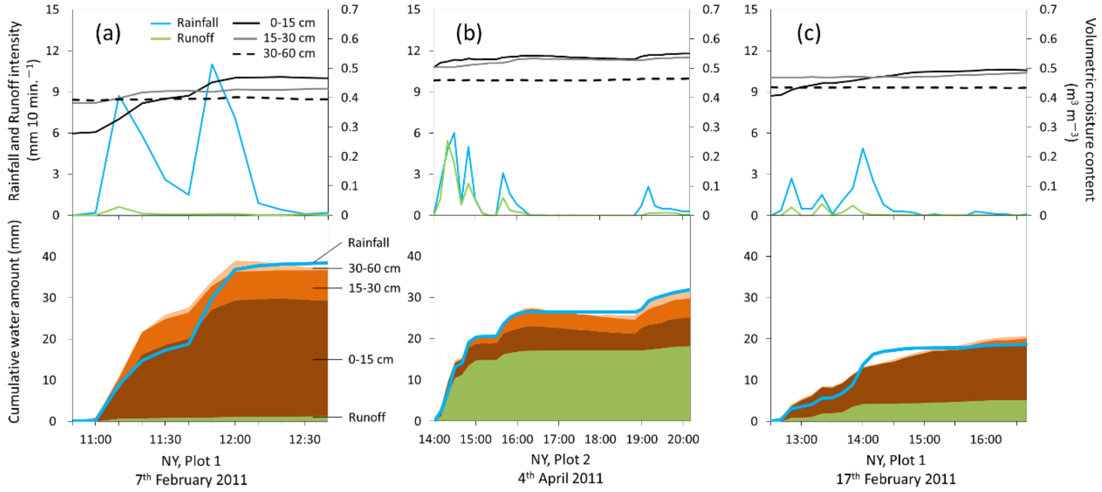

Figure 3.4 Water budget during rainfall events with different initial surface moisture conditions. Upper graph shows intensity of rainfall and surface runoff (mm per 10 min) and volumetric moisture content at each depth. Lower graph shows cumulative water amount derived from rainfall in each proportion. (a) Rainfall event when initial surface moisture condition was Dry. Because soil moisture content in the surface layer (0–15 cm) increased, surface runoff generation was suppressed. (b) Rainfall event when initial moisture condition was Wet. 0–15 and 15–30 cm layers were nearly saturated at rainfall event onset. Rainfall could not therefore infiltrate into the ground and runoff ratio became large. (c) Rainfall event when the initial surface moisture condition was Moist. Some rainfall infiltrated while another part ran off.

Table 3.4 Multiple regression models of runoff amounts at four sites.

Site	Variables	Coefficient	Delta r^2	p
NY	Constant	-8.25		
(n = 43)	log(Rainfall)[b]	4.54	0.150	0.022
	Initial VWC	14.97	0.079	0.050
	Cum. r^2		0.229	
TA	Constant	-8.18		
(n = 43)	Duration	0.00	0.314	<0.001
	Initial VWC	29.08	0.072	0.037
	Cum. r^2		0.386	
SO	Constant	-5.61		
(n = 23)	Duration	0.01	0.604	<0.001
	Initial VWC	33.23	0.067	0.057
	Cum. r^2		0.671	
MA[a]				

[a] All variables have been eliminated at MA (n = 25).
[b] Rainfall amount was transformed by taking the logarithm not to reject normality.

could not hold water anymore because of little pore space, giving a large runoff ratio 57.0% (Fig. 3.4b). In the case where the antecedent moisture condition was moist, part of the rainfall infiltrated and the other part intermediately ran off (Fig. 3.4c). The runoff ratio of this event was 22.3%.

The results of regression analysis are shown in Table 3.4. No significant correlation between runoff and independent variables was found at MA. 22.9% of the variation in runoff could be accounted for by rainfall amount and initial VWC of rainfall events at NY, while 38.6% and 67.1% could be accounted for by duration and initial VWC of rainfall events at TA and SO, respectively. All sites had initial VWC as one of the covariates with a relatively high coefficient for runoff amount, which partly corresponded to the results in Fig. 3.3 showing runoff suppression at dry soil moisture condition.

3.3.4 Soil loss and sediment concentration in surface runoff water at the four sites

Daily soil loss was generally greater in the latter half of the rainy season (February–May) at the four sites, because rainfall amounts increased (Fig. 3.2). Total soil loss was 36.1, 47.3, 15.9, and 22.8 Mg ha^{-1} at NY, TA, SO and MA, respectively (Table 3.2).

The ratio of total soil loss to total runoff amount (total sediment concentration) is shown in Table 3.2. Total sediment concentration was 23.0, 26. 2, 17.8, and 36.4 g L^{-1} at NY, TA, SO and MA, respectively, and the concentration at MA was twice than at SO.

Soil loss and sediment concentration through the experimental period had no significant correlation with environmental parameters (rainfall amount, average, minimum and maximum VWC and average and maximum I_{10}) at all sites, except soil loss with rainfall amount at SO.

Table 3.5 Pearson's correlations coefficients between soil losses and environmental parameters at each antecedent soil moisture condition at the four sites

	NY								
	Dry (n = 4)			Moist (n = 4)			Wet (n = 4)		
	Rainfall	I10_max	I10_ave	Rainfall	I10_max	I10_ave	Rainfall	I10_max	I10_ave
Sediment concentration	-0.358	0.531	0.943 *	0.878	0.184	-0.123	-0.503	-0.884	-0.425
Soil loss	-0.138	0.733	0.998 ***	0.591	0.569	0.230	-0.085	0.251	0.462
	TA								
	Dry (n = 6)			Moist (n = 7)					
	Rainfall	I10_max	I10_ave	Rainfall	I10_max	I10_ave			
Sediment concentration	0.926 ***	0.420	0.619	-0.272	0.448	-0.118			
Soil loss	0.952 ***	0.255	0.519	0.009	0.451	-0.066			
	SO								
	Dry (n = 14)								
	Rainfall	I10_max	I10_ave						
Sediment concentration	0.114	0.023	0.065						
Soil loss	0.54 **	0.008	-0.192						
	MA								
	Dry (n = 1) and Moist (n = 10)								
	Rainfall	I10_max	I10_ave						
Sediment concentration	0.476	0.398	-0.235						
Soil loss	0.594 *	0.235	-0.216						

SO consists of only dry condition. MA consists of dry and moist condition, but there was only one dry condition so that statistical analysis was conducted for all together.
*** Positive correlation at 0.01 level.
** Positive correlation at 0.05 level.
* Positive correlation at 0.1 level.

However, there was significant correlation when antecedent soil moisture condition was dry (Table 3.5). At NY, soil loss and sediment concentration were significantly correlated with average I_{10} within rainfall events when antecedent soil moisture condition was dry. Total rainfall amount within rainfall events had significant correlation with soil loss at TA, SO and MA, and with sediment concentration at TA, when antecedent soil moisture condition was dry.

3.4 Discussion

3.4.1 Relationship between surface runoff generation and soil and rainfall properties

Soil physical properties of the surface layer substantially affected the runoff ratio at each site. Low K_s and high VWC of the surface layer in the middle of the rainy season caused low infiltration capacity, and this resulted in a large runoff ratio at NY. However, low bulk density at TA and a lot of large size pores through the depths at TA and MA resulted in high K_s and consequently caused low runoff ratios compared to those at NY. At SO, the runoff ratio was the highest of the four sites (16.6%). VWC below 30 cm depth at SO did not fluctuate through the rainy season, although it had high K_s as measured in the soil core samples collected before the rainy season. This is likely because K_s was reduced by soil crust formed during the rainy season (Morin and Benyamini, 1977).

Surface runoff generation was inhibited when the antecedent soil moisture condition was dry at all sites except SO, regardless of rainfall amount in the events (Fig. 3.3). This is also partly indicated by the multiple regression model that showed initial VWC was one of the covariates for runoff amount at all sites except MA (Table 3.4). The trend is consistent with those reported by Le Bissonnais et al. (1995) and Ziadat and Taimeh (2013), who conducted erosion experiments using simulated rainfall in the field and the laboratory. When the antecedent soil moisture condition was dry, the stronger hydraulic gradient caused a higher infiltration rate into the surface layer, and surface runoff generation was suppressed (Fig. 3.4a). Because of the coincidence of increase of VWC at the 0–15 cm depth and depression of runoff amount (Fig. 3.4), the runoff ratio largely depended on the dry-wet state and water holding capacity (i.e. unsaturated pore volume) of the surface layer. In addition to the water balance of three rainfall events shown in Fig. 3.4, water budget at four sites basically followed the trend for each antecedent soil moisture condition, although there were a few events in which the cumulative amount of soil water content and runoff amount was lower than the rainfall amount. This was probably because of the missing data for soil water content due to bypass flows or the underestimation of runoff amount due to heavy rainfall.

However, surface runoff mostly occurred immediately after onset of the rainfall events at all sites, even in dry conditions when infiltration capacity was presumably high. Moreover, high rainfall intensity that exceeded K_s of surface soil was recorded only at NY, where K_s was the minimum of the four sites. Although K_s of surface soil in cropland is generally high compared with rainfall intensity, indicating that surface runoff generation should theoretically be restricted in most cases, this was not the case in our study. This is probably because of the factors reducing the infiltration rate of the surface soils during rainfall events, such as air entrapment (Suhr et al., 1984; Kwaad and Mulligen, 1991) or crust formation (Bradford et al., 1987; Moore and Singer, 1990; Le Bissonnais and Singer, 1992). It is also possible that soil water repellence can be a cause of increased runoff generation in dry soils, as was found for organic unburnt (Santos et al., 2013) and burnt soils (Malvar et al., 2015; Prats et al., 2013).

3.4.2 Relationship between soil loss and soil and rainfall properties

Both sediment concentration and soil loss had significant correlation not with rainfall amount but with average I_{10} within sampling periods at NY (Table 3.5), indicating that soil loss occurred during storms with high intensity. This also indicated that the soil surface at NY had relatively high tolerance against detachment by rainfall and surface runoff because of sealing (Le Bissonnais and Singer, 1992), which enhanced runoff generation and consequently increased sediment concentration as the erodibility increased. Total sediment concentration was lowest at SO (17.8 g L^{-1}), suggesting high tolerance against detachment probably due to soil crust formation as well as runoff generation at SO. Rainfall amount was correlated with soil loss at SO and MA (Table 3.5), and cumulative soil loss at both sites mostly increased in the later rainy season (Fig. 3.1), when there was more than the twice rainfall amount that fell in the first half. The high erosion susceptibility of the sandy soil at MA resulted in the highest total sediment concentration regardless of its low I_{10} and runoff ratio (Tables 3.1 and 3.3). At TA, both sediment concentration and soil loss had significant correlation with rainfall amount (Table 3.5). The highest rainfall amount, in addition to the highest I_{10}, through the experimental period at TA (Table 3.3) substantially caused the highest soil loss in the four plots (Table 3.2).

Total soil loss during the experimental period at NY and TA was high compared with the foothill sites SO and MA. The former (mountainous) sites had a much higher slope gradient, a higher rainfall amount, and a slightly higher rainfall intensity, generating greater surface runoff water, regardless of runoff ratio. Despite lower sediment concentrations at NY and TA, runoff amounts were sufficiently large to overcome the soil loss at MA with the highest sediment concentration. These results suggest that the pluviometric gradient in the current study area is playing an important role in describing the water erosion characteristics (Ruiz-Sinoga et al., 2010; Ruiz-Sinoga and Romero-Diaz, 2010).

3.4.3 Water erosion characteristics and influences under different soil and climate conditions in Uluguru Mountains

Total soil losses observed at the four sites (15.9－47.3 Mg ha^{-1}), even when not considering the loss during the dry season, were similar or low compared with other erosion experiments in Tanzania. Ligonja and Shrestha (2015) predicted 14.7 to 23.0 Mg ha^{-1} $year^{-1}$ of soil erosion in the Kondoa area using USLE. Ngatunga et al. (1984) observed 38, 93, and 88 Mg ha^{-1} $year^{-1}$ soil losses at bare sloping sites with 10, 19 and 22% slope gradients, respectively, in the Usambara Mountains of northeastern Tanzania. Kimaro et al. (2008) also conducted erosion experiments in maize cropland with 30–70% slope gradients on the northern slopes of the Uluguru Mountains, and reported 69 and 163 Mg ha^{-1} $year^{-1}$ of soil losses by interrill and rill erosion, respectively. The reason for the low total soil losses in the present study can be attributed to the gentle slope at the research sites and less disturbance of the soil surface. In addition, longer plot lengths and results including rill erosion might have contributed to the greater soil loss in the other studies. However, soil loss, especially at the mountainous sites (NY and TA), was much greater than the soil-loss tolerance values, which indicate acceptable rates of soil erosion to be 1.4–12 Mg ha^{-1} (Schertz, 1983; Montgomery, 2007; Verheijen et al., 2009).

NY had the lowest K_s of the surface soil layers (Table 3.1) and that layer was saturated from the middle to end of the rainy season (Fig. 3.1); therefore, the runoff ratio became large despite the low average I_{10}. In addition, the rainfall amount was substantial at this site, resulting in a large runoff amount (Table 3.2). Although sediment concentration was intermediate, which increased with rainfall intensity of rainfall events (Table 3.5), large amounts of runoff resulted in high soil loss (Table 3.2).

At TA, the high K_s of surface and sub-surface layers caused rapid drainage of infiltrated water to deeper layers and resulted in the lowest runoff ratio of the four sites during the experimental period (Table 3.2). However, large amounts of rainfall and the high rainfall intensity generated the greatest runoff amount and soil loss of the four sites (Table 3.2 and 3.3). Large amount of soil loss was also caused by rainfall amount in addition to the high intensity. Mulching is therefore effective to protect the ground surface against raindrop impacts and to enhance the infiltration of rain water and water holding capacity (Mulumba and Lal, 2008; Jordán et al., 2010; Cerdà et al., 2016), especially in the early rainy season when the area covered by crops is limited.

Although SO had high K_s, its runoff ratio was the largest of the four sites. Moreover, total soil loss was the least because sediment concentration was the lowest of the four sites (Table 3.2). This unique water erosion characteristic is probably a result of soil crust formed during the rainy season. Soil loss was correlated with rainfall amount (Table 3.5), and most of the soil loss occurred during large rainfall events in the later rainy season (Fig. 3.1). The importance of soil preservation was highlighted in this period.

MA had low rainfall amounts and generally small runoff ratios, and therefore the total runoff amount was small (Table 3.2). However, the water erosion risk was high over the rainy season, considering sediment concentration was the highest of the four sites and soil loss was correlated with the rainfall amount (Fig. 3.1, Table 3.5). Taking into account the high erosion susceptibility of the sandy soil at MA, in addition to the surface protection with mulch, it is necessary to suppress soil loss with spatial managements, e.g. contour farming (Quinton and Catt, 2004).

3.5 Conclusion

Water erosion by measuring the water budget and soil loss for entire rainfall events at four sites was evaluated in the Uluguru Mountains area of Tanzania, and revealed that water erosion characteristics were highly variable because of different soil and rainfall properties. Runoff generation was related to rainfall amount and infiltration capacity, which were represented by large runoff amounts at NY with low K_s and at TA despite its high K_s, where rainfall amount was greater than in the foothill sites, SO and MA. Dry soil moisture conditions at the beginning of rainfall events also contributed to suppressed runoff generation. Sediment concentration were related to rainfall amount and intensity at the mountainous sites, NY and TA, and soil texture was also one of the factors which enhanced sediment concentration at the sandy site, MA. Soil loss was regulated by runoff amount and sediment concentration, and thus high runoff amounts due to high rainfall amounts at NY and TA which resulted in greater soil losses compared to that at the foothill sites. It is, therefore, suggested that the land management retaining the soil structure and the drainage capacity of the surface soil, e.g., surface mulching or cover crop, is principally important to suppress water erosion under various environmental conditions in the Uluguru Mountains.

CHAPTER 4
CO_2 FLUX AND SOIL CARBON STOCK UNDER DIFFERENT QUALITY AND APPLICATION METHODS OF CROP RESIDUES IN MAIZE CROPLANDS WITH CONTRASTING SOIL TEXTURES IN MOROGORO, TANZANIA

4.1 General

Soil carbon (C) plays a central role in the soil quality in tropical agroecosystems where strongly weathered soils with low nutrient holding capacity is dominant, and the application of organic materials is essential to increase soil organic matter because it represents the dominant reservoir and source of plant nutrients (Zech et al., 1997). However, the high temperature and the high activity of soil microorganisms enhance the decomposition of soil organic matter and result in low C content in soil in tropical agroecosystems.

The application of organic materials, such as crop residues and farmyard manure, is the management which farmers can afford to improve soil fertility in their croplands in SSA. The quality of applied materials regulates the decomposition patterns. The decomposition rate of organic matter depends on its biodegradability represented by its N content, C-to-N ratio, and lignin and polyphenol content (Nicolardot et al., 2001; Palm et al., 2001; Baijukya et al., 2006). Further, the application methods (i.e., incorporation or mulching) by which crop residues are located into soils will also affect the water regime around residues and surface soil (Zeleke et al., 2004; Dahiya et al., 2007) and the contact area of residues with soil. The application methods therefore could subsequently influence the decomposition and nutrient release rates of the crop residues (Schomberg et al., 1994; Stemmer et al., 1999). Generally, decomposition rate of mulched residues is lower than that of incorporated residues because they have smaller area of attachment to the soil and are subjected to alternating wet and dry periods that may restrict microbial activity (Coppens et al., 2006). However, mulching can suppress evaporation and remain soil moisture condition high especially in top layer compared with incorporation (Dahiya et al., 2007), which can mitigate the decreases of microbial activity in the surface soil and the rate of organic matter decomposition through drying surface soil due to a high evaporation rate in the tropics. Therefore, the change of decomposition processes of applied residues need to be evaluated with special reference to soil moisture dynamics along with rainfall patterns under natural condition in the field experiment.

Table 4.1 Soil physical and chemical properties of surface and subsurface layers at the clayey and sandy sites.

Site	Depth	Clay	Silt	Sand	pH	EC	CEC	Total C	Total N	Total P	Resin P	Exc. K	Exc. Na	Exc. Ca	Exc. Mg
	(cm)	(%)				(μS cm^{-1})	(cmol$_c$ kg^{-1})	(g C kg^{-1})	(g N kg^{-1})	(mg P kg^{-1})		(cmol$_c$ kg^{-1})			
Clayey site	0–15	29	13	57	5.8	34.3	9.9	11.8	0.94	484.6	19.0	0.81	0.08	5.80	9.10
	15–30	38	12	51	5.6	30.0	10.5	8.5	0.66			0.41	0.05	5.40	2.59
Sandy site	0–15	3	5	92	5.0	12.2	1.7	3.1	0.25	72.2	7.3	0.15	0.08	0.54	0.24
	15–30	2	5	93	5.0	10.6	1.4	2.1	0.16			0.15	0.06	0.40	0.22

Abbreviations: EC, Electric conductivity; CEC, Cation exchangeable capacity; Exc., Exchangeable.
Particle size distribution: Clay (<0.002 mm); silt (0.002–0.05 mm); sand (0.05–2 mm).

Soil physicochemical properties will also affect the decomposition process of applied organic matters. The region of SSA has various soil types, which have developed under a variety of environmental conditions (Jones et al., 2013). These soils greatly differ in soil texture, organic matter content, water retention properties and the ability to mineralize C and N (Iqbal et al., 2015), and therefore the decomposition pattern of the applied residue can greatly vary with those various soil properties in SSA. Generally, soil texture is known to be an important factor that controls the process of decomposition of organic matter because soil texture regulates the water- and nutrient-holding capacities and the microbial activities in soils (Van Veen and Kuikman, 1990; Sugihara et al., 2010b; Sugihara et al., 2012b). The effect of soil types with different physicochemical properties need to be evaluated.

The effect of application of organic materials on SOM in tropical agroecosystems is, therefore, still debatable. Thus, the objective in this study was to evaluate the effects of application method and quality of crop residues on CO_2 flux and soil C stock at the two maize croplands with contrasting soil textures in Tanzania.

4.2 Material and methods

4.2.1 Description of study sites

Field experiments were conducted for two years from March 2012 to February 2014 at two sites with different soil textures, i.e., SO (29% clay), and MA (3% clay). Soil physicochemical properties at the beginning of the experimental period are shown in Table 4.1.

4.2.2 Experimental design

The experimental design included the following five treatments:

(1) Ctrl plot: control (no residue input);

(2) F plot: chemical fertilizer-treated plot (urea equivalent to 40 kg N ha^{-1});

(3) M-In plot: maize residue-incorporated into soil in the plot (5.0 Mg ha^{-1} on a dry basis of maize straw and leaf equivalent to 2.4 Mg C ha^{-1} and 40 kg N ha^{-1}; C:N ratio = 60);

(4) M-On plot: maize residue-mulching in plot (same amount as the M-In plot);

(5) P-In plot: cowpea residue incorporation into the soil in the plot (2.7 Mg ha^{-1} on a dry basis of cowpea straw and leaf equivalent to 0.8 Mg C ha^{-1} and 40 kg N ha^{-1}; C:N ratio = 21).

The detailed description of the cultivation experiment was shown in Chapter 2. The experimental period was from March 2012 to February 2014 (24 months). I counted a year from March to February; year 2012 from March 2012 to February 2013, and year 2013 from March 2013 to February 2014 since the residues were applied in March every year.

4.2.3 Environmental monitoring

Volumetric soil water content (VWC) and soil temperature at a depth of 5 cm were measured continuously in the Ctrl plot with time domain reflectometer probes (CS616 Water Content Reflectometer; Campbell Scientific, Inc., Logan, UT, USA) and thermistor probes (Model 108 Temperature Probe; Campbell Scientific, Inc.), respectively. The probes for VWC had two replications, while those for soil temperature had no replication. Rainfall amounts (TE525 Tipping Bucket Rain Gage; Campbell Scientific, Inc.) and air temperature (Model 108 Temperature Probe; Campbell Scientific, Inc.) were also measured at each site. All sensors were connected to a datalogger (CR1000; Campbell Scientific, Inc.), and data were recorded at 10-minute intervals at each site.

4.2.4 Soil sampling and analyses

Soil samples were collected from the layers of 0-5 and 5-15 cm two times, i.e. in March 2012 and February 2014, to estimate the C stock in the surface soil. Soil samples from a depth of 0–15 cm were taken using a stainless core (300 cm^3 with 15 cm height) in five replicates, which were randomly selected inside the plot (7 × 7 m; avoiding the edge of the plot). Each sample was divided into two segments, 0–5 cm and 5–15 cm, and five respective subsamples were composited and mixed per replication. Each composited sample was weighed for measuring the bulk density. Soil samples were sieved (< 2 mm), air dried, then ovendried at 100°C for 24 h, and milled in a ball mill (MM200, Retsch). The C content was measured using a dry combustion method with an NC analyzer (Vario Max CHN, Elementar).

4.2.5 Measurement of CO_2 efflux rate and estimation of annual CO_2 flux

CO_2 efflux rate was measured by a closed-chamber system at a frequency of approximately 2 weeks in the rainy season and 1 month in the dry season at both the clayey and sandy sites. 35 times measurements are conducted at both sites over the experimental period (March 2012 to February 2014, 24 months). PVC columns (diameter 13 cm, height 30 cm) were inserted randomly in each plot after plant residue application. PVC columns were vertically installed into the surface soil to a depth of 15 cm, and the enclosed soil was later covered with a fine plastic mesh to support the soil in the PVC column sample and to maintain the same soil moisture condition as outside the PVC column.

The annual CO_2 flux was estimated by a modified Arrhenius relationship between the measured CO_2 efflux and soil moisture content monitored by the sensors, as follows (Sugihara et al., 2012b),

$$Cem = a\, M^b$$

where *Cem* is the hourly CO_2 efflux rate (mol C ha^{-1} h^{-1}), *M* is the volumetric water content (m^3 m^{-3}), *b* is a coefficient related to the contribution of soil moisture, and *a* is a constant. In current study, soil moisture content and soil temperature in F and P-In plots were substituted with that of C and M-In plot, respectively.

Decomposed residue amount was calculated from the difference of the CO_2 flux between the Ctrl plot and the crop residue-applied plot, and the decomposition rate was calculated as the ratio of the decomposed amount to the applied amount.

4.2.6 Data analysis

All statistical analyses were performed with SigmaPlot 11.0 software (Systat Software, Inc., San Jose, CA, USA). All data are expressed on a dry-weight basis. To assess the environmental factors that control the seasonal fluctuation in CO_2 efflux rate in the Ctrl plot, Pearson's correlation coefficient was applied to soil moisture and air/soil temperature data. To assess the effects of plant residue application, and fertilizer application on CO_2 efflux rate throughout the experimental period, two-way repeated-measures analysis of variance (RM-ANOVA) was used for both clayey and sandy sites. This same ANOVA paradigm was used to assess the effects of plant residue application and fertilizer application on soil moisture content, data for which were collected periodically. In addition, Tukey's test was used to assess differences in (1) averaged CO_2 efflux rate in the Ctrl plot between clayey and sandy sites, and (2) surface soil C stock (0-15 cm) between the March 2012 and February 2014 samples between treatments. One-way ANOVA was also used to assess the significance of differences in changes of surface soil C stock for each treatment in February 2014. When ANOVA indicated significant differences, mean comparisons were performed with the Tukey-Kramer multiple comparison test. Surface soil C stock was calculated by multiplying soil C content by soil bulk density in each plot. In all cases, $p < 0.05$ was considered significant.

4.3 Results

4.3.1 Environmental factors

The annual rainfall amount was higher at the clayey site than that at the sandy site in 2012 and 2013 (Table 4.2), and they were less than the average value observed in the previous years, i.e., ~750 mm (Sugihara et al., 2012a). The rainy season, November to June, had substantially higher amount of rainfall compared with the dry season, July to October, at both the sites. Following the rainfall variation, VWC at 5 cm depth in the all plots decreased during the dry season, and increased in the rainy season, especially from March to June during the cultivation period (Fig. 4.1). The application of crop residues generally increased the soil moisture content

Table 4.2 Coefficients for estimating CO_2 flux and rainfall amount in 2012 and 2013 at the clayey and sandy sites.

Treatment	Year	n	ln(a)	a	b	r^2		Rainfall (mm) Total	Mar.—Jul.	Aug.—Feb.
Clayey site										
Ctrl	Mar. 2012 - Feb. 2013	18	4.78	119.5	1.41	0.43	**	485	275	210
	Mar. 2013 - Feb. 2014	17	4.39	80.3	0.95	0.48	**	479	234	245
F	Mar. 2012 - Feb. 2013	18	4.90	134.3	1.41	0.59	***			
	Mar. 2013 - Feb. 2014	17	6.09	443.2	1.74	0.43	**			
M-In	Mar. 2012 - Feb. 2013	18	5.50	243.5	1.49	0.71	***			
	Mar. 2013 - Feb. 2014	17	6.30	542.9	1.72	0.54	***			
M-On	Mar. 2012 - Feb. 2013	18	5.65	284.9	2.01	0.35	**			
	Mar. 2013 - Feb. 2014	17	5.72	305.8	1.53	0.45	**			
P-In	Mar. 2012 - Feb. 2013	18	5.34	209.0	1.59	0.27	*			
	Mar. 2013 - Feb. 2014	17	5.71	300.8	1.54	0.34	**			
Sandy site										
Ctrl	Mar. 2012 - Feb. 2013	17	3.39	29.5	0.45	0.26	*	332	177	155
	Mar. 2013 - Feb. 2014	17	3.54	34.5	0.40	0.19	*	431	261	171
F	Mar. 2012 - Feb. 2013	17	3.87	48.0	0.51	0.28	*			
	Mar. 2013 - Feb. 2014	17	4.01	55.0	0.41	0.40	**			
M-In	Mar. 2012 - Feb. 2013	17	4.85	128.0	0.70	0.50	***			
	Mar. 2013 - Feb. 2014	17	5.78	324.7	0.89	0.38	**			
M-On	Mar. 2012 - Feb. 2013	17	4.76	116.7	0.71	0.59	***			
	Mar. 2013 - Feb. 2014	17	6.46	641.0	1.06	0.50	***			
P-In	Mar. 2012 - Feb. 2013	17	4.33	75.9	0.63	0.20	*			
	Mar. 2013 - Feb. 2014	17	5.28	195.4	0.75	0.43	**			

N shows the numbers of sampling time.
*** Positive correlation at 0.001 level.
** Positive correlation at 0.01 level.
* Positive correlation at 0.05 level.

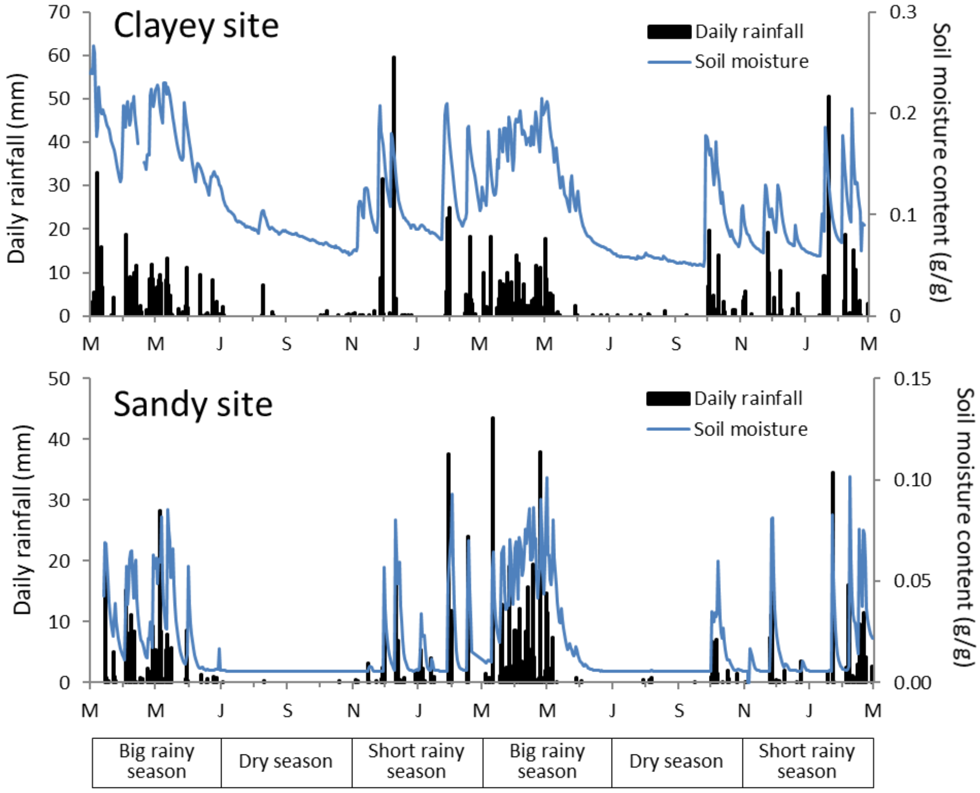

Figure 4.1 Daily rainfall and soil moisture content at the clayey and sandy sites over the experimental period.

compared with the plot without residue at both sites. During the cropping season, soil moisture content directly measured on each soil sampling day rarely showed significant differences among the treatments at both the clayey and sandy sites (Fig. 4.2). However, at the clayey site, the soil moisture content in the M-On plot was higher than those in the 0–5 cm layer in the Ctrl and F plots on 0 DAP in 2012 and that in the 5–15 and 0–5-cm layers in the Ctrl plot on −9 and 45 DAP in 2012, respectively. These occasional increases of soil moisture content in the M-On plot indicated that residue mulching had suppressed water lost through evaporation. At the sandy site, the soil moisture content in the entire soil layer (0–30 cm) in the M-On plot was significantly higher than that in the Ctrl plot in both 2012 and 2013, while that in the F, M-In, P-In plots had no significant difference with that in the Ctrl plot.

Soil temperatures gradually increased in the dry season (July to November), and started decreasing in the rainy season (March to June, Fig. 4.3), and it was always above 20°C throughout the experimental period at the clayey and sandy sites. The average daily soil temperature in the M-On plot (27.5°C) was significantly lower than that in the Ctrl plot (28.1°C) and the M-In plot (28.3°C) at the clayey site, while that in the Ctrl, M-In, and M-On plots (29.6–29.8°C) had no difference at the sandy sites.

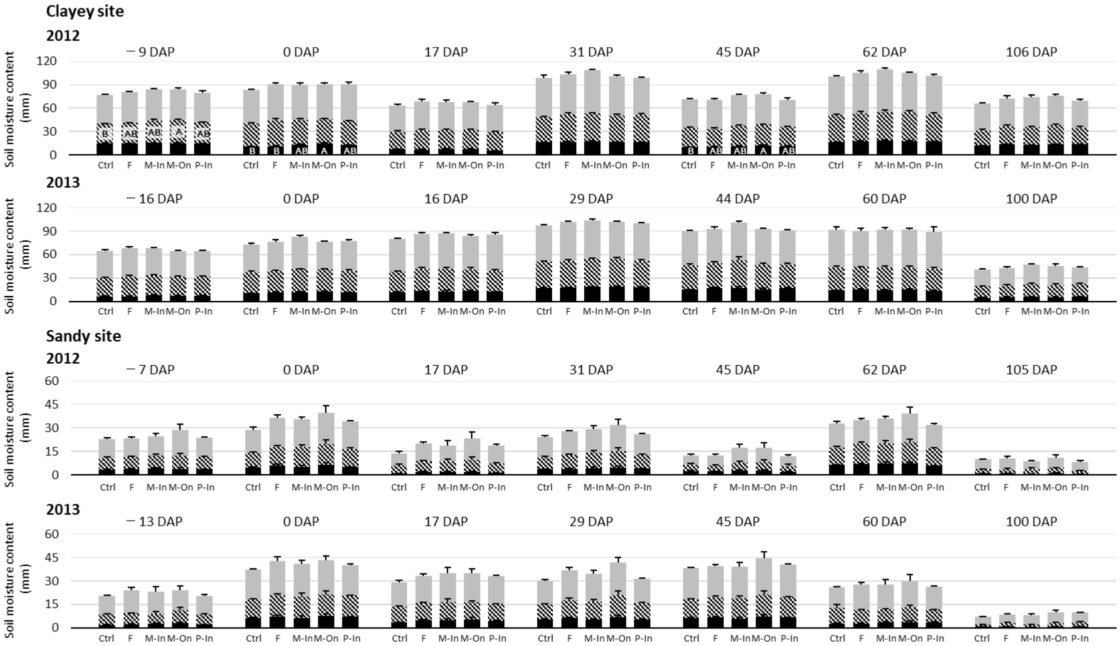

Figure 4.2 Soil moisture content in the surface layers in the treatment plots on each sampling day (mm). Bars indicate: Black bar, 0–5 cm soil layer; Slashed, 5–15 cm soil layer; Grey, 15–30-cm layer. Different letters (A and B) indicate significant differences among the treatments in each soil layer at each study sites on each sampling day. Error bars indicate the standard error. Abbreviations: DAP, days after planting; Ctrl, control (no residue input); F, chemical fertilizer-treated plot; M-In, maize residue-incorporated plot; M-On, maize residue-mulching plot; P-In, cowpea residue-incorporated plot.

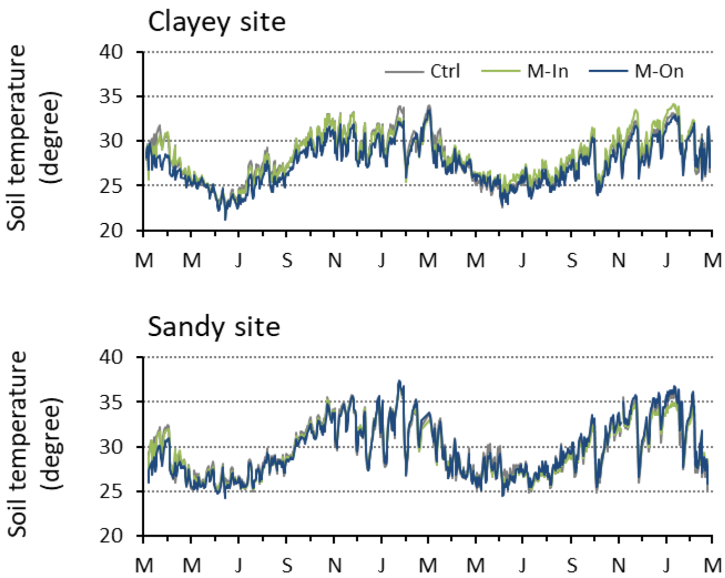

Figure 4.3 Daily soil temperatures in the Ctrl, M-In, and M-On plots at the clayey and sandy sites over the experimental period.

4.3.2 Seasonal fluctuation of CO_2 efflux rate

Fig. 4.4 shows the fluctuation in soil respiration (CO_2 efflux rate) in 2012 and 2013 at the clayey and sandy sites. CO_2 efflux rate in all the treatment plots was relatively high during the cropping season (March to June) while it was low during the dry season.

At the clayey site, significant differences of CO_2 efflux rate among the treatment plots were observed until second week (0 DAP) in 2012 and sixth week (28 DAP) in 2013 after cultivation and residue application. The averaged CO_2 efflux rate in the residue-applied plots (i.e., M-In, M-On and P-In plots) were significantly higher than that in the Ctrl and F plots. Further, the averaged CO_2 efflux rate was higher in maize residue applied plots, especially in the M-In plot, compared to that in the cowpea residue applied plot. In addition, the averaged CO_2 efflux

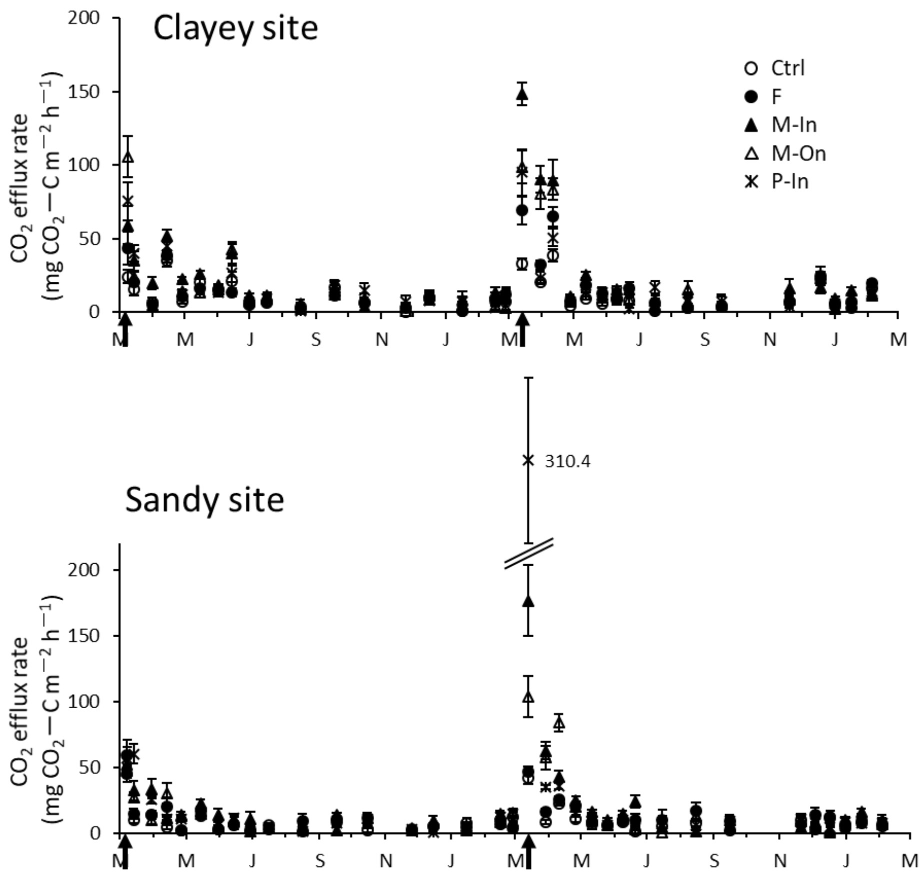

Figure 4.4 Fluctuations in rainfall and soil moisture and fluctuations in CO_2 efflux rate over the experimental period at the clayey and sandy sites. Arrows indicate the date of the crop residue application. Bars indicate standard error. M-In: Maize residue-incorporated plot, M-On: Maize residue-mulching plot, P-In: Cowpea residue-incorporated plot, F: Chemical fertilizer-treated plot, and C: Control plot.

rate in the F plot significantly increased compared with that in the Ctrl plot in 2013 at the clayey site.

At the sandy site, significant differences of CO_2 efflux rate among the treatment plots were observed until third week (17 DAP) in 2012 and sixth week (29 DAP) in 2013 after cultivation and residue application. The CO_2 efflux rate was highest in the P-In plot on the first sampling day after the application (0 DAP), the M-In plot on the second sampling day after application (17 DAP in both years), and the M-On plot on the third sampling day after application (31 DAP in 2012 and 29 DAP in 2013). The averaged CO_2 efflux rate in the F plot significantly increased compared with that in the Ctrl plot in 2013 at the sandy site.

4.3.3 Estimation of annual CO_2 flux

Estimated annual CO_2 flux in all the treatment plots at both the sites are shown in Fig 4.5. Annual CO_2 flux ranged from 0.7−2.0 Mg C ha^{-1} yr^{-1} at the clayey site, and from 0.4−1.7 Mg C ha^{-1} yr^{-1} at the sandy site. The CO_2 flux during the big rainy season accounted for a half of the total annual CO_2 flux while that during the dry season accounted for 20% at both the clayey and sandy sites (Fig. 4.5). Annual CO_2 flux in the M-In, M-On and P-In plots was higher than that in the Ctrl plot.

The difference in the annual CO_2 flux between the Ctrl plot and the residue-applied plot was assumed to be derived from the decomposition of residue. The estimated amount of the decomposed residue was shown in Table 4.3, and the decomposition rate was calculated by the ratio of the decomposed amount to the original amount. The decomposition rate was 34, 14 and 49% in the M-In, M-On and P-In plots, respectively, at the clayey site, and 19, 26 and 41% in the

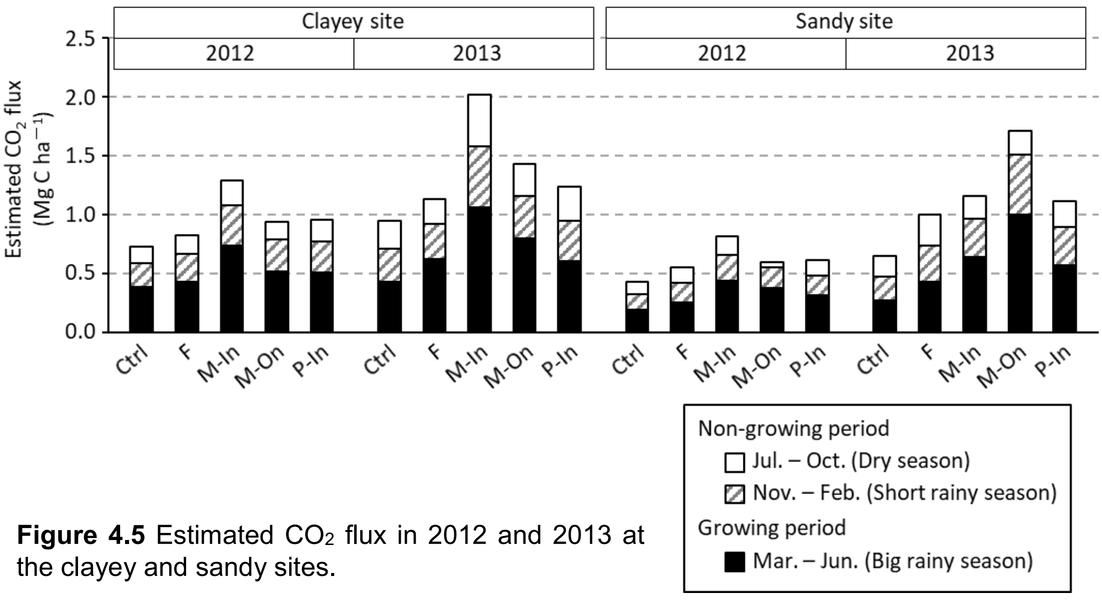

Figure 4.5 Estimated CO_2 flux in 2012 and 2013 at the clayey and sandy sites.

M-In, M-On and P-In plots, respectively, at the sandy site.

4.3.4 Soil carbon stock

Soil carbon stocks in the 0-15 cm layer in March 2012 and February 2014 are shown in Table 4.3. Soil C stock at the clayey site, ranging from 27.7 to 30.9 Mg C ha^{-1}, was significantly larger than that at the sandy site, ranging from 6.9 to 10.4 Mg C ha^{-1}. Significant difference in soil C stock was not observed among treatments and sampling dates ($p > 0.05$).

4.4 Discussion

4.4.1 Environmental factors controlling CO_2 flux

Soil respiration rate was not controlled by soil temperature in all the treatment plots although soil temperature was significantly lower in the plots with maize residues, i.e., the M-In and M-On plots, at both the clayey and sandy sites (Fig. 4.6). Therefore, the variation of soil respiration rate was explained only by soil moisture content influenced by rainfall in our study; 27−71% at the clayey site and 19−59% at the sandy site. This was also reported by many studies in tropical agroecosystems where the soil temperature is normally around the optimum condition for microbial activity (Panosso et al., 2009; Mapanda et al., 2010; Sugihara et al., 2012b). The high soil moisture content in addition to the disturbance by cultivation caused the high CO_2 efflux rate during the crop growing period at both sites in 2012 and 2013. On the other hand, soil moisture content mostly decreased below −98.0 kPa (pF 3.0) during the dry period, and thus CO_2 efflux rate was also suppressed during this period in all the treatment plots at the clayey and sandy sites in 2012 and 2013. As a result, 53−46% and 45−43% of the annual CO_2 flux in the

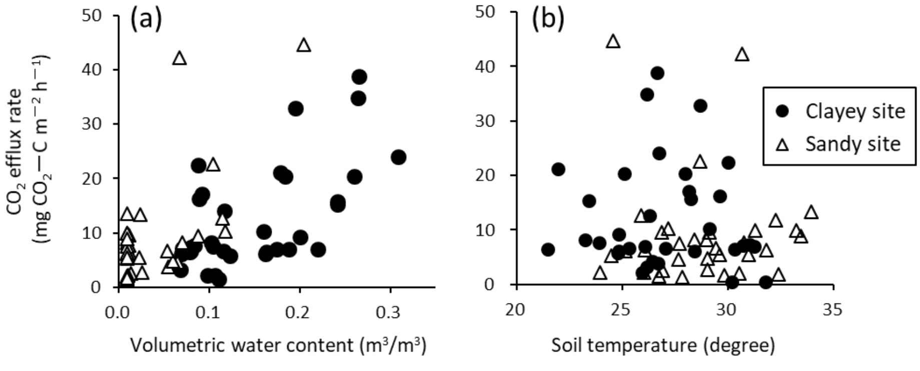

Figure 4.6 Relationship between CO_2 efflux rate and (a) soil moisture and (b) soil temperature in the Ctrl plot at the clayey and sandy sites for the two-year experimental period. CO_2 efflux rate correlated significantly with soil moisture at both sites ($P < 0.001$; for clayey, $r = 0.62$, $n = 35$; for sandy, $r = 0.67$, $n = 34$), but it did not correlate with soil temperature at either site, according to Pearson's correlation analysis.

Ctrl plot at the clayey and sandy sites, respectively, was observed in the crop growing period (March to June) as 48－60% of annual rainfall was observed during this period. The lower soil moisture content in the Ctrl plot in 2012 compared with 2013 caused the smaller soil CO_2 flux in 2012 than that in 2013 at the both site. Because of a little rainfall in both 2012 and 2013 at both the clayey and sandy sites, which was ca. 60% of mean annual rainfall, the estimated CO_2 flux in the Ctrl plot was about the half of that reported at the same sites in the previous study with 799– 905 mm of annual rainfall (Sugihara et al., 2012b). This indicated that CO_2 flux estimated in this study was strongly suppressed by the low soil water content due to the low rainfall amount in 2012 and 2013.

4.4.2 Effect of application method of crop residues on soil respiration rate and CO_2 flux

The application of crop residues, regardless of application method or quality, significantly increased the average CO_2 efflux rate compared with the plot without the application of crop residues. The increase of soil respiration rate due to the addition of substrate through the organic matter application has been reported by many others (e.g. Sugihara et al., 2012b). At the

Table 4.3 Summary of carbon budget and the change in soil carbon stock for the two-year experimental period at the clayey and sandy sites.

Treatment	C input as crop residue (Mg C ha^{-1})	C output as CO_2 flux (Mg C ha^{-1})	Decomposed residue amount (Mg C ha^{-1})	Soil C stock (Mg C ha^{-1}) Mar. 2012	Feb. 2014
Clayey site					
Ctrl	0.0	1.7		27.7 (0.9)	28.8 (1.5)
F	0.0	2.0	0.3	28.8 (1.7)	29.2 (0.5)
M-In	4.8	3.3	1.6	28.9 (1.2)	30.9 (0.6)
M-On	4.8	2.4	0.7	29.1 (1.3)	29.4 (1.8)
P-In	1.7	2.5	0.8	27.7 (0.3)	29.3 (1.0)
Sandy site					
Ctrl	0.0	1.1		6.9 (0.1)	7.1 (0.4)
F	0.0	1.6	0.5	8.0 (0.4)	9.2 (0.5)
M-In	4.8	2.0	0.9	7.5 (0.9)	8.8 (1.3)
M-On	4.8	2.3	1.2	8.5 (1.1)	10.4 (1.4)
P-In	1.7	1.7	0.6	8.0 (0.5)	8.4 (0.4)

Decomposed residue amount was calculated by the difference in C output as CO_2 from the Ctrl plot.
The values given in parentheses are standard error (N = 3).

clayey site, the mean value of soil efflux rate during the experimental period in the M-In plot was significantly higher than that in the M-On plot. It is generally said that the larger contact area of the incorporated residues with soil enhanced the decomposition by soil microorganisms (Stemmer et al., 1999) while the mulched residues had less contact area and are subjected to the drier condition compared with the incorporated residues (Coppens et al., 2006). However, the difference in the soil respiration rate between the M-In and M-On plots was relatively small during the dry season because the dry soil moisture condition in the surface layer suppressed even the decomposition of incorporated residues at the clayey site. Unlike at the clayey site, the incorporation was not profitable for the residues to be surrounded by moist soils even during the cropping season due to the originally low water holding capacity of sandy soils, while the mulching of residues contributed to maintain the higher soil moisture content at the sandy site. Meanwhile, at the sandy site, the mean value of soil efflux rate during the experimental period had no significant difference between the M-In and M-On plots. These results likely suggested that CO_2 efflux rate obtained in the M-On plot was derived more from the decomposition of the original SOM, which generally has narrow C:N ratio compared with maize residue, and less from the decomposition of the applied residues compared with the M-In plot. It was partly supported by the results of soil inorganic N dynamics discussed in Chapter 5, which showed the larger increase of soil inorganic N in the M-On plot than in the M-In plot.

As the soil respiration rate was strongly controlled by the soil moisture content (Fig. 4.6), the estimated CO_2 flux in each treatment plot substantially reflected the change in the soil moisture content influenced by the rainfall distribution and the residue application method. Soil CO_2 flux was observed mainly in the crop growing period (March to June) at both the sites; 53－46% and 45－43% of the annual flux in the Ctrl plot at the clayey and sandy sites, respectively. This indicated the high microbial activity in soils during this period due to the adequate soil moisture condition and the residual effect of initial cultivation. At the clayey site, the total decomposed amount was 2.3 times higher in the M-In plot than the M-On plot, which is consistent with the results of CO_2 efflux rate. Coppens et al. (2006) conducted a laboratory incubation experiment using mature oilseed rape labelled with ^{13}C and a silt loam soil, and reported that the amount of ^{13}C mineralized from surface residues was only 66% of the amount of ^{13}C mineralized from incorporated residues after 9 weeks of incubation. At the sandy site, the dry soil moisture condition suppressed the soil respiration in all the plots even with crop residues in 2012 because of a little amount of rainfall (332 mm), and it resulted in the small difference in the annual soil CO_2 flux between the M-In and M-On plots. However, the soil moisture was higher in the M-On plot especially during the big rainy season. It suggested, therefore, that the decomposition rate of the applied residue which was calculated from the difference between the M-On and Ctrl plots might be overestimated, and the larger decomposition of the original SOM in the surface layer in the M-On plot would be considered.

4.4.3 Effect of quality of crop residues on soil respiration rate and CO_2 flux

The high biodegradability and the high mineralization capacity of cowpea residues resulted in prompt increase of CO_2 efflux rate in the P-In plot. A short increase of the CO_2 efflux rate was observed soon after the application of residues in the P-In plot at both the clayey and sandy sites. Frimpong et al. (2011) also reported the rapid decomposition rate of cowpea residues compared with maize residues during the first week after incorporation under controlled laboratory conditions using a tropical luvisol. The high quality of cowpea residues attributed to its narrow C:N ratio could cause quick decomposition and release of nutrient in soils after the application (Franzluebbers et al. 1994a; Abera et al., 2012). The results suggested that the applied cowpea residue could play a significant role as a resource of nutrient especially in the early stage of the growing season, which will be discussed in Chapter 5. On the other hand, the annual decomposition rate of cowpea-residue over the experimental period was 1.4 and 2.2 times larger than that of maize residue at the clayey and sandy sites, respectively.

The application of chemical fertilizer significantly increased the CO_2 efflux rate in 2013 and the estimated CO_2 flux during the growing period in 2012 and 2013 compared with that in the Ctrl plot at the clayey and sandy sites. The decomposition of the labile soil organic matter was stimulated by the addition of urea, which increased the soil microbial activity. Knorr et al. (2005) showed the stimulated decomposition due to N enrichment at field sites exposed to low ambient N deposition and for high-quality (low-lignin) litters based on the meta-analysis. However, the significant difference in the CO_2 efflux rate between the Ctrl and F plots was rarely observed during the dry season when soil moisture content was continuously less than -98.0 kPa. It suggested that the decomposition of the soil organic matter is primarily limited by the soil moisture content in the dry condition rather than the N availability. This result is consistent with Franzluebbers et al. (1994b) which suggested that intermittent periods of dry soil between rainfall events could result in the reduced decomposition of applied residues.

4.4.4 Carbon budget and soil carbon stock under different quality and application method of crop residues

Input of C in the P-In plot (0.8 Mg C ha^{-1}) was one third of that in the M-In and M-On plots (2.4 Mg C ha^{-1}) because of the narrow C:N ratio of the cowpea residue. Cumulative soil respiration over the experimental period in the Ctrl plot was the lowest among the treatments, and this was supposed to be the basal soil respiration at each site. Cumulative soil respiration over the experimental period in the M-In plot was 34 and 14% higher than that in the P-In plot at the clayey and sandy sites, respectively, while the decomposition rate in the P-In plot was 15 and 22% higher than that in the M-In plot at the respective sites. At the clayey site, the decomposition rate of the applied maize residue in the M-On plot was decreased by 19% (0.5 Mg C ha^{-1} yr^{-1}) compared with that in the M-In plot. On the other hand, at the sandy site, cumulative soil respiration substantially varied with the annual rainfall amount, and it had no clear difference among the application methods, incorporation vs mulching, over the two-year experiment. The balance of C amount of the applied residue (input) and the cumulative CO_2 flux (output) over the two-year experimental period was neutral or negative in the Ctrl, F, and P-In plots and positive in the M-In and M-On plots at both the clayey and sandy sites (Table 4.3). These results suggested that the application of maize residues had potential to increase, or maintain at least, soil C stock under a little rainfall and dry soil moisture condition at both the clayey and sandy sites.

However, neither significant increase nor decrease in soil C stock in the surface layer was detected after the two-year experimental period, and soil C stock had no difference among the treatment plots at both the beginning and the end of the experimental period. This could be attributed to the large spatial variance of soil C stock at the experimental sites, where standard error for soil C stock was comparable with the C output as CO_2 flux in the Ctrl plot over the two-year experimental period. Further study is needed to determine the effect of the application of crop residues on soil C stock with a long-term experimental period, and required to evaluate the effect of the high rainfall amount on the soil CO_2 flux and the decomposition rate of the applied residues.

4.5 Conclusion

The total CO_2 flux in the maize-incorporation (M-In) plot was 39% higher than that in the maize-mulching (M-On) plot at the clayey site, while the M-On plot had 17% higher CO_2 flux than the M-In plot at the sandy site. The high soil moisture content in the M-On plot at the sandy site suggested that the higher contribution of SOM decomposition to the CO_2 flux in the M-On plot compared with that in the M-In plot. Cowpea residues had twice high decomposition rate compared with that of maize residues reflecting its high biodegradability. Based on the C balance of the applied residue (input) and the cumulative CO_2 flux (output) over the two-year experimental period, the application of maize residues with a realistic amount which farmers can afford showed the possibility to increase, or maintain at least, soil C stock under a little rainfall and dry soil moisture condition at both the clayey and sandy sites.

CHAPTER 5
SOIL NITROGEN DYNAMICS UNDER DIFFERENT QUALITY AND APPLICATION METHODS OF CROP RESIDUES IN MAIZE CROPLANDS WITH CONTRASTING SOIL TEXTURES IN MOROGORO, TANZANIA

5.1 General

Soil nitrogen (N) is the most important limiting factor related to crop production in low-input agriculture of Sub-Saharan Africa (SSA), where low soil fertility is causing poor crop production (Hartemink et al., 2000; Chikowo et al., 2004; Mapanda et al., 2012). Because of the economic conditions and unstable climatic conditions in SSA, local small land holders use only small amounts of chemical fertilizers (Nyamangara et al., 2003). Therefore, the input of crop residues, which are available after harvesting crops, is one of the strategies that farmers can afford to improve crop production. The application of crop residue can improve soil N dynamics through the improvement of water- and N-use efficiency as well as the input of the substrate of soil organic matter (SOM) (Dormaar and Carefoot, 1996; Palm et al., 2001; Sugihara et al., 2010b; Sugihara et al., 2012a) with a variety of management controlling influential factors, i.e., the quality, quantity, timing and location of inputs of crop residues to the soil (Palm et al., 2001).

As described in Chapter 5, the decomposition process of applied crop residues varies along the application method and quality of residues and soil types especially during the cropping season. The nutrient release from the residues would greatly differ with those factors, and therefore it is important to investigate the time course of microbial activity, the increase of soil N that resulted from the decomposition of applied residues, and the N uptake by crops in tropical croplands. Coppens et al. (2007) and Iqbal et al. (2015) reported that the decomposition of mulch was primarily limited by moisture and not by quality of the applied organic matter in laboratory experiments at a temperate of 20°C. Nevertheless, most of the previous researches associated with organic matter application and N dynamics in soils were conducted under controlled conditions in the laboratory, and few field experiments have been conducted to reveal their effects on the dynamics of soil inorganic N and crop N uptake especially in SSA.

Understanding the influence of crop residue management and soil types on the decomposition process and soil N dynamics based on field experiment is critical for improving crop yield in SSA. The objective of this study is therefore to investigate the crop residue management in terms of quality and application method to improve soil N dynamics during the period of crop growth in maize croplands with special reference to soil textures in Tanzania.

5.2 Material and methods

5.2.1 Description of study sites

Field experiments were conducted from March 2012 to June 2013 at two sites with different soil textures in Tanzania, i.e., SO (29% clay), and MA (3% clay). Soil physicochemical properties are shown in Table 4.1.

5.2.2 Field experimental design

The experimental design included the following five treatments:

(1) Ctrl plot: control (no residue input);

(2) F plot: chemical fertilizer-treated plot (urea equivalent to 40 kg N ha^{-1});

(3) M-In plot: maize residue-incorporated into soil in the plot (5.0 Mg ha^{-1} on a dry basis of maize straw and leaf equivalent to 2.4 Mg C ha^{-1} and 40 kg N ha^{-1}; C:N ratio = 60);

(4) M-On plot: maize residue-mulching in plot (same amount as the M-In plot);

(5) P-In plot: cowpea residue incorporation into the soil in the plot (2.7 Mg ha^{-1} on a dry basis of cowpea straw and leaf equivalent to 0.8 Mg C ha^{-1} and 40 kg N ha^{-1}; C:N ratio = 21).

The detailed description of the cultivation experiment was shown in the section 2.2.2 in Chapter 2.

5.2.3 Monitoring environmental factors

Volumetric soil water content (VWC) and soil temperature at a depth of 5 cm were measured continuously in the Ctrl plot with time domain reflectometer probes (CS616 Water Content Reflectometer; Campbell Scientific, Inc., Logan, UT, USA) and thermistor probes (Model 108 Temperature Probe; Campbell Scientific, Inc.), respectively. The probes for VWC had two replications, while those for soil temperature had no replication. Rainfall amounts (TE525 Tipping Bucket Rain Gage; Campbell Scientific, Inc.) and air temperature (Model 108 Temperature Probe; Campbell Scientific, Inc.) were also measured at each site. All sensors were connected to a datalogger (CR1000; Campbell Scientific, Inc.), and data were recorded at 10-minute intervals at each site.

5.2.4 Soil sampling and analyses

Soil samples were collected at −14, 0, 28, 45, 60 and 105 DAP using a stainless core and an auger. Soil samples from a depth of 0–15 cm were taken using a stainless core (300 cm^3

with 15 cm height) in five replicates, which were within 10 cm of the plants randomly selected inside the plot (7 × 7 m; avoiding the edge of the plot). Each sample was divided into two segments, 0–5 cm and 5–15 cm, and five respective subsamples were composited and mixed per replication. Each composited sample was weighed for measuring the bulk density, while the bulk density of 15-30-cm layer was measured at the beginning of the experimental period in both 2012 and 2013. Samples from a depth of 15–30 cm were taken very close to the point where the core sample had been collected using an auger again using five replicates from each plot, and the five subsamples were composited and mixed per replication. After passing through a 4-mm sieve, the soil samples were held in a refrigerator until the following analyses was conducted.

A part of the soil samples was dried in an oven of 105°C for 24 h and then weighed to measure the soil moisture content. Inorganic N (NH_4^+-N and NO_3^--N) was extracted from 10 g soil (dry base) with 30 mL of 1 mol L^{-1} KCl for 30 min on an orbital shaker, and the suspension was centrifuged (2000 *g*) and filtered through filter paper (Advantec No. 5C, Tokyo, Japan). Both NH_4^+-N and NO_3^--N concentrations were measured using a continuous flow injection analyzer (AS-50; Aqualab Co., Ltd., Tokyo, Japan) based on the modified indophenol blue method (Rhine et al., 1998) for NH_4^+ and the modified Greisess-Ilovay method (Mulvaney, 1996) for NO_3^-. Inorganic N content in each layer per unit area (kg N ha^{-1}) was calculated by inorganic N concentration, bulk density and depth of each layer.

5.2.5 Soil respiration as microbial activity in situ

At both the SO and MA sites, soil respiration (CO_2 efflux rate) was measured in all plots in the field using a closed-chamber system at a frequency of approximately 2 weeks (Sugihara et al., 2012b). Detail procedure was described in the section 5.2.5 in Chapter 5.

5.2.6 Plant sampling and analyses

Sampling of aboveground plants was conducted on 14, 28, 45, 60 and 105 DAP. Five plant samples, which were chosen randomly in the respective plots, were collected. The plant material was divided into leaf, stem, cob and grain, and dried in a greenhouse for a week and then in a 70°C oven for 48 h, and the dry matter of each part was weighed. Subsample of each part was ground, and N concentration of each part was measured using a dry combustion method with an NC analyzer (Vario Max CHN, Elementar, Hanau, Germany). The N content of each part was calculated based on its weight and N concentration, and all the N contents of four parts were summed up for total N content of aboveground biomass (crop N). Data are expressed on an area basis (kg N ha^{-1}) by multiplying the N content of each plant by the number of plants per unit area. To estimate crop yields, an additional 30 cobs of maize per replicate were collected and weighed on the last day of sampling.

5.2.7 Statistical analyses

The effects of treatment and sampling time (seasonal effect) were assessed using repeated-measured analysis of variance. The Tukey's test was used to detect statistically significant differences between treatments ($p < 0.05$). All variables were tested for normality of the distribution and transformed when necessary to minimize variation. All statistical analyses were performed with SigmaPlot 11.0 software (Systat Software, Inc., San Jose, CA, USA). All data are expressed on a dry-weight basis.

5.3 Results

5.3.1 Environmental factors

The total rainfall amount during the experimental period (March–June) was 272.2 mm (2012) and 233.4 mm (2013) at the clayey site, and 177.2 mm (2012) and 260.1 mm (2013) at the sandy site. Irrigation was applied from April to June in 2013 at both sites, the amount of applied water was 80 mm in total. Compared with the average rainfall amount during the same period at

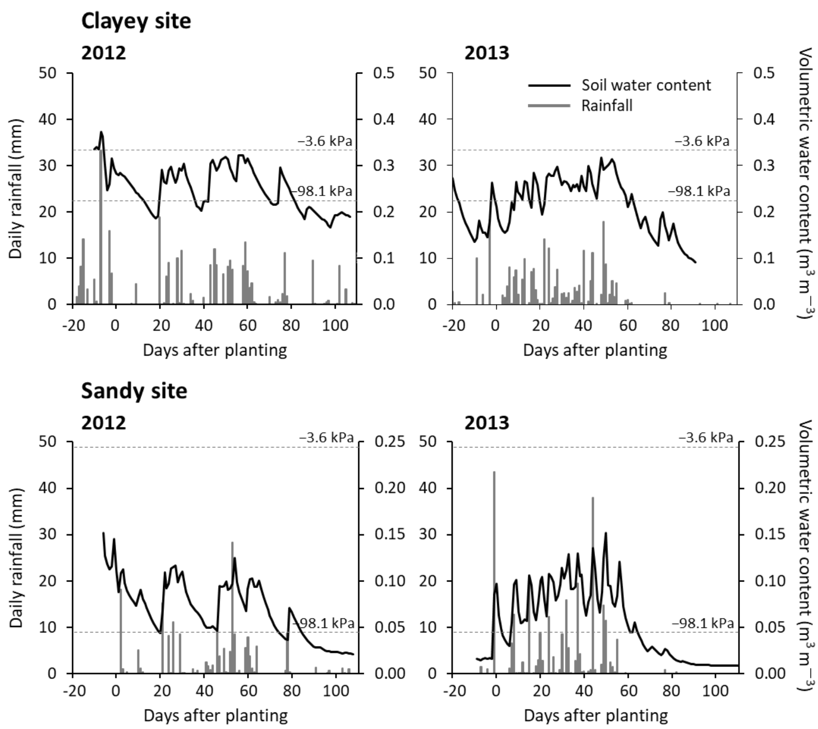

Figure 5.1 Daily rainfall and volumetric water content (5 cm depth) in the control plot at the clayey and sandy sites. Broken lines show the volumetric water contents at the matric potential (−3.6 and −98.1 kPa) at each site.

both sites, i.e., ~450 mm (Sugihara et al., 2012a), the amounts of rainfall and irrigation were substantially low in both years at both sites. While rainfall was evenly distributed throughout the experimental period at both sites in 2012, the rainfall in the early half of the experimental period until 45 DAP in 2013 included 79.3% (185.0 mm) and 84.3% (219.2 mm) of all rainfall during the experiment at the clayey and sandy sites, respectively. VWC at a depth of 5 cm at the sandy site was continuously lower than that at the clayey site throughout the experimental period (Fig. 5.1).

Soil moisture content directly measured on each soil sampling day rarely showed significant differences among the treatments at both the clayey and sandy sites (Fig. 4.2 in Chapter 4). However, at the clayey site, the soil moisture content in the M-On plot was higher than those in the 0–5 cm layer in the Ctrl and F plots on 0 DAP in 2012 and that in the 5–15 and 0–5-cm layers in the Ctrl plot on −9 and 45 DAP in 2012, respectively. These occasional increases of soil moisture content in the M-On plot indicated that residue mulching had suppressed water lost through evaporation. At the sandy site, the soil moisture content in the entire soil layer (0–30 cm) in the M-On plot was significantly higher than that in the Ctrl plot in both 2012 and 2013, while that in the F, M-In, P-In plots had no significant difference with that in the Ctrl plot.

5.3.2 Temporal variations in soil respiration

At the clayey site, significant differences in the CO_2 efflux rate among the treatment plots were continuously observed until the second week (0 DAP) and the sixth week (28 DAP) after the cultivation and residue application in 2012 and 2013, respectively (Fig. 5.2). A significant difference between the F and Ctrl plots was occasionally observed at the clayey site, whereas it was not observed throughout the experimental period in both years at the sandy site. At the clayey site, a significant increase in the CO_2 efflux rate compared with the Ctrl plot was observed in the M-In plot until 0 and 28 DAP in 2012 and 2013, respectively, and a significant increase compared with the Ctrl plot was observed in the M-On plot until −6 and 28 DAP in 2012 and 2013, respectively, as well. In contrast, a high CO_2 efflux rate was observed in the P-In plot compared with the Ctrl plot until 0 DAP in both years for a shorter period than that in the M-In plot. After the soil respiration equilibrated after 44/45 DAP, a significantly higher CO_2 efflux rate was observed on 90 DAP in the M-In and M-On plots in 2012 compared with the Ctrl plot at the clayey site. Cumulative CO_2 flux was the highest in the M-In plot, followed by the M-On, P-In, F and Ctrl plots in both 2012 and 2013 (Table 5.1).

At the sandy site, fluctuation in the CO_2 efflux rate was much less in 2012 because of its small rainfall amount compared with 2013. Significant differences in the CO_2 efflux rate among the treatment plots were observed until the fifth week (31 DAP) and the sixth week (29

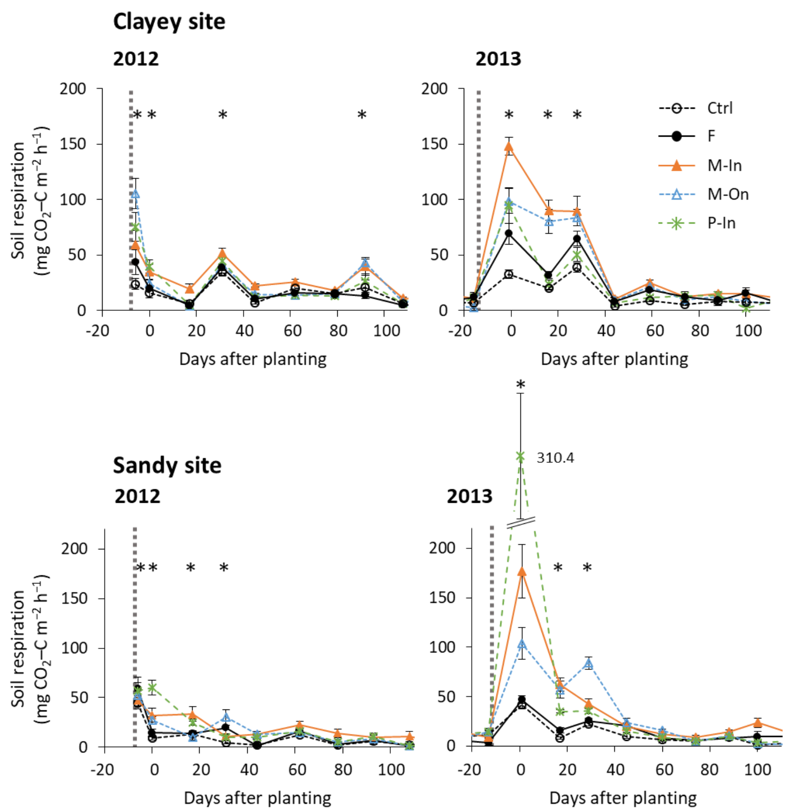

Figure 5.2 Fluctuations in soil respiration rate at the clayey and sandy sites (mg CO_2–C m^{-2} h^{-1}). Vertical broken lines show the date of residue application. * indicates significant differences among the treatments. Bars indicate the standard error.

DAP) after cultivation and residue application in 2012 and 2013, respectively, at the sandy site. A significant increase in the CO_2 efflux rate compared with the Ctrl plot was observed on 0 and 17 DAP in 2012 and 2013 in the M-In plot, and was observed on 0 and 31 DAP in 2012 and 0, 17 and 29 DAP in 2013 in the M-On plot. Furthermore, a significant increase in the CO_2 efflux rate was observed in the P-In plot on 0 DAP for a relatively short period compared with that of the plots where maize residue was applied, similar to that observed at the clayey site. Cumulative CO_2 flux was the highest in the M-In plot in 2012 while that was in the M-On plot in 2013 at the sandy site (Table 5.1).

5.3.3 Temporal variations in soil inorganic N

At the clayey site, soil inorganic N in the entire soil layer (0–30 cm) in the Ctrl plot increased significantly from −9 DAP and −16 DAP in 2012 and 2013, respectively, to 0 DAP in 2012 and 16 DAP in 2013 because of the cultivation (Fig. 5.3). At the clayey site, soil inorganic N in the entire soil layer (0–30 cm) in the F plot largely increased from 0 to 17/16 DAP and was caused by the application of fertilizer. During that period, a significant increase was observed only in the

15–30 cm layer in 2012, while a significant increase was also observed in all three layers (0–5, 5–15, and 15–30 cm) in 2013. At the clayey site, soil inorganic N in the entire soil layer (0–30 cm) in the M-In and M-On plots had no difference from that of the Ctrl plot over the experimental period in both years. In the P-In plot, a significant increase of soil inorganic N content in each three layers (0–5, 5–15, and 15–30 cm) was observed from −9/−16 DAP to 0 DAP at the clayey site in 2012 and 2013, respectively. At both the clayey and sandy sites, the soil inorganic N in the entire soil layers in all treatment plots decreased after the tasseling stage (ca. 60 DAP) to the end of the experimental period in both years, except at the clayey site in 2012.

Table 5.1 Cumulative CO_2 flux, crop N uptake, and yield at harvest in 2012 and 2013 at the clayey and sandy sites.

		Cumulative CO_2 flux ($kg\ C\ ha^{-1}$)	Decomposed residue[1)] ($kg\ C\ ha^{-1}$)	Crop N[2)] ($kg\ N\ ha^{-1}$)		Final NUE[3)] (%)	Grain yield ($Mg\ ha^{-1}$)	
Clayey site								
2012	Ctrl	374		57.3	(4.7)		2.9	(0.2)
	F	420		84.1	(12.9)	67	3.8	(0.5)
	M-In	715	340	63.4	(8.3)	15	3.2	(0.3)
	M-On	503	128	56.0	(5.6)	−3	2.7	(0.3)
	P-In	531	157	74.7	(8.4)	44	3.6	(0.4)
2013	Ctrl	421		58.0 b	(7.7)		2.2 b	(0.2)
	F	619		112.8 a	(13.9)	137	4.1 a	(0.3)
	M-In	1040	619	56.2 b	(4.5)	−4	2.1 b	(0.5)
	M-On	791	370	50.1 b	(4.6)	−20	1.8 b	(0.2)
	P-In	757	336	78.5 ab	(0.8)	51	3.0 ab	(0.1)
Sandy site								
2012	Ctrl	193		21.1 c	(3.1)		0.8 d	(0.1)
	F	257		59.8 a	(1.7)	97	2.6 a	(0.1)
	M-In	441	248	25.9 c	(5.5)	12	1.0 cd	(0.2)
	M-On	375	182	32.6 bc	(3.8)	29	1.4 bc	(0.1)
	P-In	316	124	44.9 ab	(2.9)	60	1.9 b	(0.1)
2013	Ctrl	269		11.8	(2.0)		0.4	(0.1)
	F	418		30.5	(3.1)	47	1.3	(0.2)
	M-In	630	361	15.1	(3.7)	8	0.7	(0.2)
	M-On	991	721	24.0	(4.8)	31	1.1	(0.3)
	P-In	565	295	21.4	(4.7)	24	0.9	(0.2)

Numbers in parentheses denote the standard error. Different letters within total crop N and grain yield in same year/site indicate significant difference among the treatment by the Tukey's test ($p < 0.05$).

[1)] Decomposed residue was estimated by the difference in the cumulative soil respiration between the Ctrl plot and the plots with crop residues, M-In, M-On and P-In.

[2)] Crop N is total N content of aboveground biomass of maize.

[3)] N use efficiency (NUE) was calculated by the difference in crop N between in the Ctrl plot and the plot with chemical fertilizer or crop residue application divided by the applied N amount.

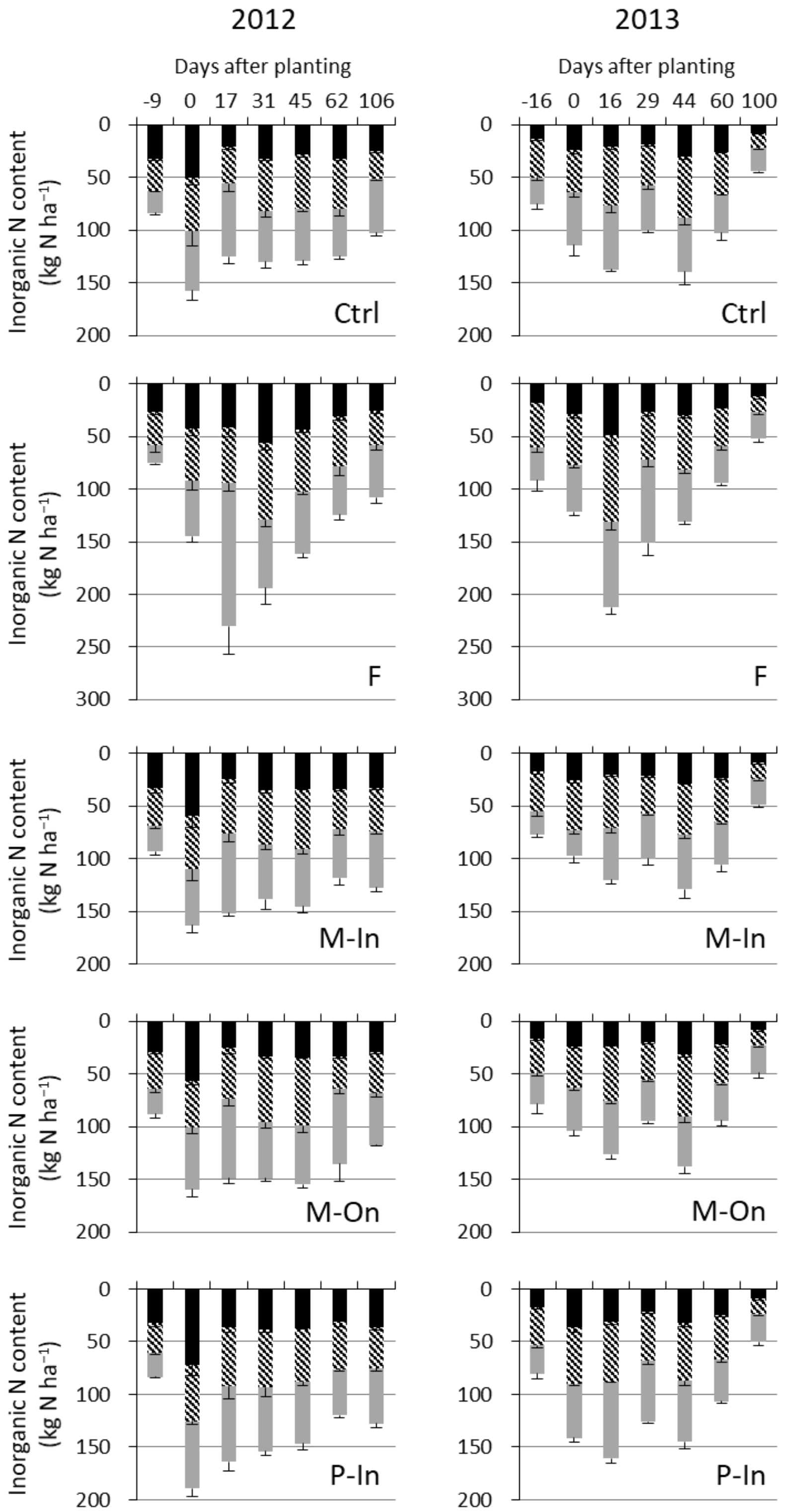

Figure 5.3 Inorganic N content in the surface layers at the clayey site (kg N ha^{-1}). Bars indicate: Black bar, 0–5 cm soil layer; Slashed, 5–15 cm soil layer; Grey, 15–30-cm layer. Bars indicate the standard error. Abbreviations: Ctrl, control (no residue input); F, chemical fertilizer-treated plot; M-In, maize residue-incorporated plot; M-On, maize residue-mulching plot; P-In, cowpea residue-incorporated plot.

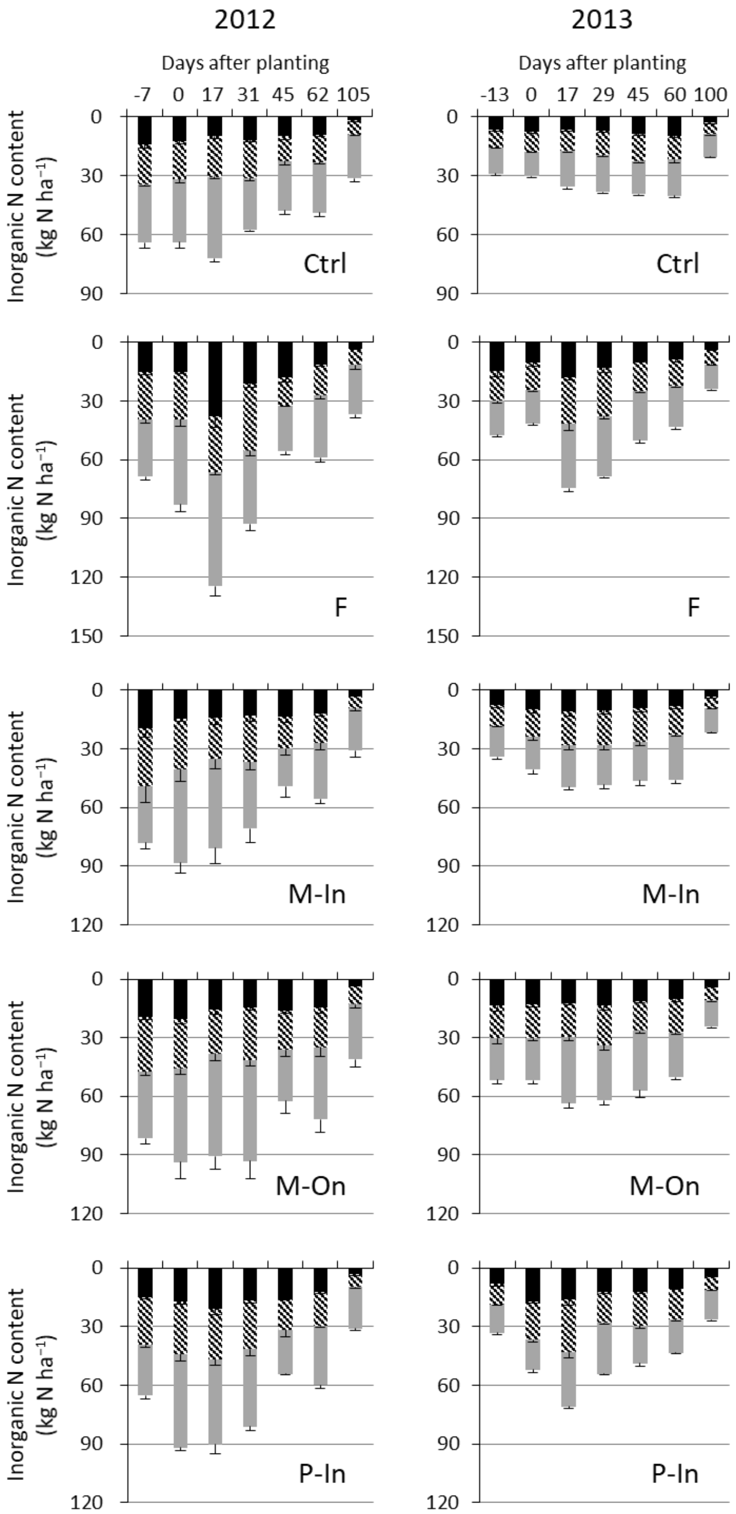

Figure 5.4 Inorganic N content in the surface layers at the sandy site (kg N ha^{-1}). Bars indicate: Black bar, 0–5 cm soil layer; Slashed, 5–15 cm soil layer; Grey, 15–30-cm layer. Bars indicate the standard error. Abbreviations: Ctrl, control (no residue input); F, chemical fertilizer-treated plot; M-In, maize residue-incorporated plot; M-On, maize residue-mulching plot; P-In, cowpea residue-incorporated plot.

At the sandy site, the soil inorganic N in the entire soil layer (0–30 cm) in all treatment plots was initially high in 2012 because of the residual effect of previous land use before the experiment (Fig. 5.4). In the Ctrl plot, soil inorganic N in the 15–30-cm layer decreased significantly from 17 to 31 DAP and that in the 0–5 and 5–15-cm layers gradually decreased from 31 to 105 DAP in 2012, while a significant decrease was observed from 60 to 100 DAP in the 0–5-cm layer in 2013. At the sandy site, soil inorganic N in the 0–5 and 15–30-cm layers in the F plot increased significantly from 0 DAP to 17 DAP in both 2012 and 2013. In the M-In plot, soil inorganic N in the 0–5 and 5–15-cm layers initially decreased from −7 to 17 DAP while that in the 15–30-cm layer increased significantly from −7 to 0 DAP in 2012 at the sandy site, indicating the downward transportation of inorganic N within the surface layer. The same trend was observed in the M-On plot as well. Soil inorganic N content in all layers (0–5, 5–15 and 15–30 cm) in the M-On plot was slightly higher than that in the M-In plot throughout most of the experimental period at the sandy site. In the P-In plot, a significant increase in soil inorganic N in the entire soil layer was observed from −7/−13 DAP to 0/17 DAP in both years at the sandy site.

5.3.4 Crop N uptake and yield

At the clayey site, total crop N decreased from 2012 to 2013 in the M-In and M-On plots (Fig. 5.5). N uptake rate by maize crop (ΔN_{crop}) in all treatments generally increased after the tasseling stage of maize (i.e., 60 DAP). ΔN_{crop} in the F plot was the highest among all treatment plots from the third to the fifth week after seeding (18–31 DAP and 17–28 DAP in 2012 and 2013, respectively), and ΔN_{crop} in the P-In plot was higher than that in the M-In, M-On and Ctrl plots during the same period. ΔN_{crop} in the P-In plot was the highest among all treatment plots from the fifth to seventh week after seeding (32–45 DAP and 29–44 DAP in 2012 and 2013, respectively). ΔN_{crop} from the tasseling stage to harvest (60–100 DAP) in 2013 was the highest in the F plot among all treatment plots, and that in the P-In plot was significantly higher than that in the M-In and M-On plots. Total crop N was the highest in the F plot, followed by the P-In, and total crop N in the M-In and M-On plots was comparable to that in the Ctrl plots in both years, while the significant differences were observed only in 2013 (Table 5.1). The crop yields followed the order of total crop N at harvest in respective years.

At the sandy site, total crop N decreased from 2012 to 2013 despite the small amount of rainfall in 2012 (Fig. 5.5). ΔN_{crop} was the highest in the F plot during 32–45 DAP and after tasseling (63–105 DAP) in 2012 followed by the ΔN_{crop} in the P-In plot, while that in the M-On plot was the highest during 46–62 DAP in 2012. ΔN_{crop} after tasseling (61–100 DAP) was highest in the F plot in 2013, followed by that in the M-On plot. Crop N uptake in the M-On plot largely increased from 46 to 62 DAP in 2012 compared with that in the M-In plot; meanwhile, the M-On

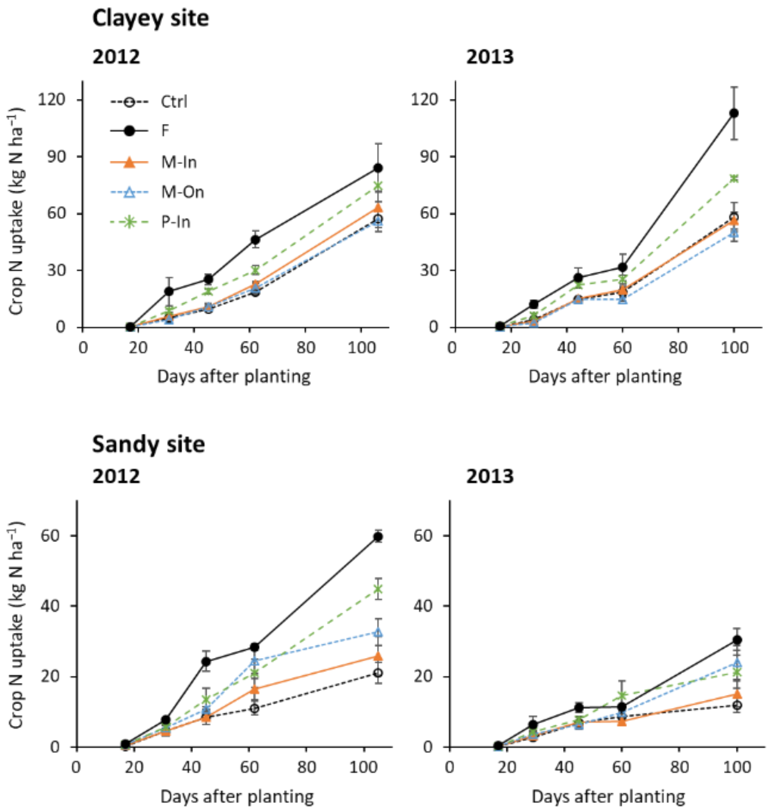

Figure 5.5 Crop N uptake at the clayey and sandy sites (kg N ha^{-1}). Bars indicate the standard error. Abbreviations: DAP, days after planting; Ctrl, control (no residue input); F, chemical fertilizer-treated plot; M-In, maize residue-incorporated plot; M-On, maize residue-mulching plot; P-In, cowpea residue-incorporated plot.

plot had a higher uptake rate after 45 DAP than the M-In plot in 2013. Total crop N was the highest in the F plot, followed by the P-In, M-On, M-In and Ctrl plots in 2012, while that was larger in the order of the F, M-On, P-In, M-In and Ctrl plots. Significant difference in crop N at harvest was observed only in 2012 at the sandy site (Table 5.1). Crop yield followed the order of total crop N at harvest in respective years.

5.4 Discussion

5.4.1 Effects of the quality of crop residues on soil inorganic N dynamic at sites with different soil textures

The mineralization of the easily decomposable SOM, which was highly caused by cultivation especially in 2012 at the clayey site, contributed to the increase of soil inorganic N in the surface layer in the Ctrl plot. At the sandy site, however, no significant increase of soil inorganic N was observed in the Ctrl plot. As indicated by the cumulative soil respiration during the experimental period, the mineralization of SOM in the Ctrl plot at the sandy site was strongly suppressed compared with that at the clayey site in 2012 because of little rainfall and low soil moisture content at the sandy site.

Quick increase of soil inorganic N in the 0–30 cm-layer following a short increase of the CO2 efflux rate soon after residue application in the P-In plot at both the clayey and sandy sites could be attributed to the high biodegradability and the high mineralization capacity of cowpea residues (Frimpong et al., 2011; Abera et al., 2012). The high inorganic N content in the entire soil layers (0–30 cm) in the early growth period in the P-In plot resulted in the high rate of N uptake by crops until the fifth (29–31 DAP) to seventh week (44–45 DAP) after seeding, especially at the clayey site. Decomposed amount of the applied residue until the fourth sampling day (ca. 30 DAP) in the P-In plot was 1.0–1.4 times at the clayey site and 1.4–2.3 times at the sandy site as high as that in the M-In plot. This result suggests rapid degradation of the applied cowpea residue, and it consisted with the rapid increase of soil inorganic N in the P-In plot. Franzluebbers et al. (1994a) also reported a rapid decomposition and nitrogen release during the first three weeks after incorporation of green manure of cowpea. The high decomposition rate of cowpea residues and the low nutrient-holding capacity of sandy soils may result in the leaching of N caused by strong rainfall events while the amount of aboveground biomass is still small in the early growth period at the sandy site.

Likewise, the application of chemical fertilizer resulted in a rapid increase in soil inorganic N in the surface soil and enhanced the rate of crop N uptake at both sites. NUE in the F and P-In plots reached 29–39% and 20–24%, respectively, on 45/44 DAP in 2012 and 2013, while those in the M-In and M-On plots were less than 4% at the clayey site, indicating the quick N absorption by crops owing to the high N availability from the high-quality fertilizer. Li et al. (2002) reported plants in manured plots extracted more water from deep soil layers by developing deeper and more extensive root systems when maize suffered from a water deficit, resulting in well-maintained physiological activity and biomass production under water stress. As observed in the current study, the rapid and high increase of soil inorganic N content and crop N in those plots during the early stage of growth in a little-rain year may suggest that the application of high quality fertilizer can improve the drought resistance of plants because of the rapid development of the root system. Consequently, final NUE was 44–51 and 67–137% in the P-In and F plots, respectively, and the high crop yield was observed in the P-In and F plots in 2012 and 2013 compared with the other plots at the clayey site.

Final NUE in the M-In plot ranging from −4% to 15% was substantially smaller than that in the P-In plot at the clayey site. However, the soil inorganic N in the 0–30-cm layer gradually increased after the application at the clayey site. In addition, considering the lack of a difference in the crop N uptake as well as the soil inorganic N pool in the 0–30-cm layer between the Ctrl and M-In plots (Figs. 5.3 and 5.5), it seems that the application of maize residue did not occur a critical N deficiency and had no effect on crop N uptake and crop yield in the M-In plot at the clayey site. Therefore, it is suggested that the application of crop residue in advance to seeding in tropical croplands can avoid N competition caused by N immobilization as reported by other studies (Yadvinder-Singh et al., 2004; Sugihara et al., 2012a).

At the sandy site, only a small increase of soil inorganic N in the layer with incorporated residue (0–15 cm) was observed. This suggests that the net N mineralization of maize residues was limited by the low availability of soil inorganic N in the surface soil at the sandy site. Recous et at. (1995) also reported that the cumulative decomposition amount of applied maize residue was reduced in the soils with low availability of soil inorganic N compared with the soils with non-limiting soil inorganic N. Final NUE in the M-In plot was substantially smaller than that in the P-In plot in both 2012 and 2013 at the sandy site. The amount of decomposed residue during the experimental period in the M-In plot at the sandy site was smaller than that at the clayey site. Sakala et al. (2000) also reported that microbial respiration was limited by N availability when maize residues were added to soil in a laboratory incubation study. Crop N and yield in the M-In plot were comparable with those in the Ctrl plot, indicating that the application of maize residue did not occur the severe N depletion at the sandy site as well as the clayey site.

5.4.2 Effects of application method of crop residues on the dynamics of soil inorganic N in soils with different soil textures

At the clayey site, the difference of application method of crop residues had no clear effect on the dynamic of soil inorganic N. There was no significant difference in the fluctuation of soil inorganic N in the surface layer (0–30 cm) between the M-In and M-On plots, and the soil inorganic N content of the two plots was not significantly different from that in the Ctrl plot throughout the experimental period in both years. Final NUE in the M-On plot was lower than that in the M-In plot in both 2012 and 2013. This could be attributed to that the amount of the decomposed maize residue during the experimental period was higher in the M-In plot (340–619 kg C ha^{-1}) than that in the M-On plot (128–370 kg N ha^{-1}) in both years. These results indicated that the application methods did not substantially change the dynamics of soil N and did not show the clear effect on crop yield at the clayey site. Meanwhile, it can be said that critical N deficiency did not occur after the application of maize residues either through incorporation or mulching. Sugihara et al. (2010a) showed that microorganism behaved as a sink of N through the decomposition of incorporated crop residue without a severe N deficiency in Tanzanian maize cropland.

In contrast to the clayey site, soil inorganic N content increased in the M-In and M-On plots compared with that in the Ctrl plot during the experiment at the sandy site, suggesting that

N deficiency did not occur in the surface layer. At the sandy site, the soil moisture content increased in the M-On plot, but not in the M-In plot (Fig. 4.2 in Chapter 4). There was little rainfall during the experimental period so that the mulched residue was dried and the decomposition was suppressed compared with that incorporated into the soil (Coppens et al., 2006). The estimated amount of decomposed residue in the M-In plot was higher than that in the M-On plot in 2012 at the sandy site. Despite the low decomposition of applied residue in the M-On plot compared with the M-In plot, the soil inorganic N content in the entire soil layer (0–30 cm) in the M-On plot slightly increased by 18% on average, but following the same fluctuation pattern, during the experimental period in 2012, and crop N uptake in the M-On plot was 1.3 times higher than in the M-In plot at the sandy site. This is probably because of the higher SOM decomposition due to the higher soil moisture condition compared with that in the M-In plot. In 2013, on the other hand, the soil inorganic N content in the entire soil layer (0–30 cm) in the M-On plot increased by 26% on average compared with that in the M-In plot during the experimental period (Figs. 5.4 and 5.5). Crop N uptake also rapidly and greatly increased in the M-On plot reflecting the higher soil inorganic N level in the surface layer. Consequently, NUE in the M-On plot was 31%, while that in the M-In plot was 8% in 2013 at the sandy site, resulting from the high crop N uptake with mulching of residue compared with the incorporation in the sandy soils. This is also supported by that CO_2 efflux rate remained significantly higher in the M-On plot for a longer period until ca. 30 DAP compared with that in the M-In plot and the cumulative CO_2 flux through the experimental period in the M-On plot was 1.6 times higher than that in the M-In plot in 2013. Incorporated residue is generally believed to have a high decomposition rate compared with mulched residue because it is surrounded by relatively wet soils (Coppens et al., 2006; Nicolardot et al., 2007), as observed at the clayey site in the current study. However, the low water-holding capacity of the top layers in the sandy soil, in which residues are incorporated, and the small amount of rainfall during the experimental period (177.2 mm and 260.1 mm in 2012 and 2013, respectively) at the sandy site probably suppressed the decomposition of SOM and applied residues and limited the increase of soil inorganic N. Thus, the mulched residue had largely contributed to prolonged relatively high soil moisture content in the surface layer and enhanced SOM decomposition compared with the incorporated residue at the sandy site. This is consistent with the observation of Coppens et al. (2007) which reported that N mineralization could be enhanced under the high moisture condition resulted by mulching based on their laboratory experiment.

5.5 Conclusion

The results showed that the incorporation of cowpea residues promptly increased soil respiration and soil inorganic N derived from the decomposition of the applied residue. This occurred within ca. 2 weeks after the application of cowpea residues at both the clayey and sandy sites, and it resulted in high NUE over the experimental period and consequent crop yield compared with those in the maize residue plots. At the clayey site, the incorporation of maize residue showed no significant difference in the dynamics of soil N compared with that in the Ctrl and M-On plots, although slightly higher soil respiration, NUE and crop yield than those in the mulching plot were observed in the M-In plot. However, mulching at the sandy site resulted in improved soil moisture content in the surface layer and then in increased soil inorganic N content during the cropping season. Soil inorganic N content in the M-On plot was mostly higher during the experimental period and consequently NUE and yield became higher than those in the incorporation plot at the sandy site. Considering the low amount of rainfall received during the two cropping seasons at both sites, ranging from 177 mm to 273 mm, it should be emphasized that the mulching of crop residue had the advantage of suppressing evaporation in the sandy soil that exhibited a low water-holding capacity and also resulted in improved soil N dynamics in a drought year.

CHAPTER 6
SUMMARY AND CONCLUSION

6.1 Evaluation of water erosion characteristics under different environmental conditions in Morogoro, Tanzania

Water erosion characteristics and the factors affecting surface runoff generation and soil loss were evaluated based on a short-term water budget and soil loss for entire rainfall events in the Uluguru Mountains. The water balance in rainfall events clearly showed that the dry soil moisture condition at the beginning of rainfall events enhanced the infiltration and suppressed runoff generation. The volume of large size pore in the surface layer, which likely controlled the permeability, was an important factor for suppressing runoff generation. The results showed that the high rainfall amounts in the mountainous areas and high susceptibility of sandy soils to erosion enhanced soil loss by water erosion. Two of the sites, NY and TA, were located in the mountainous areas and had higher rainfall amounts, resulting in the higher surface runoff and soil loss than in the two foothill sites, SO and MA. Runoff amount was related to rainfall amount, but also to infiltration capacity. Runoff ratio was low at the sites with high permeability in the surface layer, TA and MA. Sediment concentration and soil loss were basically enhanced by high rainfall amount and intensity at the mountainous sites. Although sandy soils in MA had high infiltration rate and low runoff ratio, their high susceptibility to transport by surface runoff increased its sediment concentration. On the other hand, soil crust formation apparently increased runoff ratio in NY and SO through decreasing infiltration rate, while it decreased soil loss through increasing tolerance of surface soil against detachment in SO. It is, therefore, suggested that retaining the soil structure and the drainage capacity of the surface soil is principally important to suppress water erosion under various environmental conditions in the Uluguru Mountains.

6.2 Improvement of water and nutrient dynamics using crop residues in maize croplands in Morogoro, Tanzania

The effects of application method and quality of crop residues on carbon and nitrogen dynamics in maize croplands with different soil textures were evaluated in Morogoro, Tanzania. Due to the little rainfall amount during the experimental period, the CO_2 flux was suppressed in all the treatment plots compared with that in a normal year. The results of C balance between input as crop residues and output as CO_2 flux showed that the application of maize residue with an affordable amount for local farmers had the potential to increase the soil C stock in a year with little rain at both the clayey and sandy sites. On the other hand, the results of soil C stock suggested the difficulty of detecting the effect of applying crop residues on soil C stock and the uncertainty of improving the soil quality in terms of soil organic matter in a short period in Morogoro with a substantial fluctuation of annual rainfall amount.

On the other hand, the significance of the application of crop residues was highlighted during a cropping season. During the cropping season when soil moisture content was relatively high, the decomposition rate of the incorporated maize residues was increased by 19% compared with that of the mulched residues at the clayey site because of the larger contact area of the incorporated residues. However, the application of maize residues regardless of application methods showed no difference in soil inorganic N level and crop yield compared with the plot without crop residue at the clayey site, probably because of the immobilization of inorganic N by soil microorganisms due to the addition of maize residue with high C:N ratio. At the sandy site, on the other hand, mulching of maize residue resulted in the higher soil moisture content and subsequently the higher soil inorganic N content by 18-26% compared with that in the plot with incorporated maize residue. Consequently, crop N uptake resulted in 26-59% higher in the mulching plot than in the incorporating plot at the sandy site. The incorporation of cowpea residues with high biodegradability caused prompt increase in the soil inorganic N at both clayey and sandy sites. It resulted in high N use efficiency in the early growing period and 18-73% higher total crop N uptake than that in the maize residue plots at both the sites. The optimum agricultural management using crop residues to improve water- and nutrient-use efficiency was presented for each cropping system in clayey and sandy sites.

6.3 Toward the optimum agricultural management in upland cropping systems in Morogoro, Tanzania

In the upland cropping systems in Morogoro, Tanzania, crop production is limited by low water and nutrient use efficiency and depleting soil fertility because of soil degradation. Little input of chemical fertilizer and organic matter is also the reason why soils cannot be replenished the lost nutrient. The results in this study highlighted that the water and nutrient dynamics in soils are substantially varied along the soil types and environmental conditions in a limited space in Morogoro, and, therefore, the optimum managements to increase water- and nutrient-use efficiency should be selected in places based on the water and nutrient dynamics in soils.

Application of crop residues was expected to be an essential agricultural management to preserve soils against water erosion and to increase soil fertility in tropical agroecosystems as well as many previous studies stated in temperate regions. However, this study showed the difficulty of increasing SOM by the application of crop residues with the amount which farmers can afford on their own croplands in Morogoro with a large fluctuation of annual rainfall. This is principally because of the high decomposition rate due to high soil microbial activity and high temperature in tropical agroecosystems. To increase the soil fertility in terms of soil organic matter in a long term, therefore, the application of crop residues should be re-conceptualized not only as the on-the-spot practice in a cropland but also as the area/regional management which accumulate the biomass from surrounding area to a cropland. In some regions in northern Tanzania, farmers have adopted such a management carrying and accumulating crop residues from a place to another. The efficiency and sustainability of this system using the organic matter management should be evaluated based on the C and nutrient budget in a regional scale.

In a short term, such as a cropping season, the application of crop residues played an important role for water and nutrient dynamics in soils. According to the results obtained in the sloping sites, the surface mulching with crop residues, which can retain the soil structure and the drainage capacity of the surface soil, was to be a widely applicable management to suppress water erosion under various environmental conditions in the Uluguru Mountains. In the maize cultivation experiments, on the other hand, the mulching of crop residues maintained the soil moisture for a longer period than the incorporation of residues in the sandy sites, and it resulted in high water use efficiency and high N uptake. The application of cowpea residue caused high N use efficiency especially in the early growth stage due to the prompt decomposition, and it might improve the drought tolerance through increasing water use efficiency with the rapid development of the root system compared with the application of maize residue regardless of soil types. These agricultural management using crop residues can solely or integrally be applied to improve water- and nutrient-use efficiency in the upland cropping systems in Morogoro, Tanzania.

Further studies should be addressed to examine the nutrient and water dynamics in soils after application of a mixture of different residues with contrasting biochemical properties, which could achieve much higher efficiency of water and nutrient, and to investigate quantitatively the N sources for crops whether N is derived from the applied crop residues or the original SOM, in field experiments on different soil types in Morogoro. In addition, it should be evaluated whether those agricultural managements proposed in this study can be applied to the other areas in semi-arid to sub-humid SSA under the similar environmental conditions to Morogoro.

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APPENDIX I

Table S1. Summary of rainfall and runoff for each rainfall event at NY.

Event number	Date	Duration	Initial soil water content in 0-15 cm depth (m^3 m^{-3})	Max rainfall intensity (mm 10 min.$^{-1}$)	Total rainfall (mm)	Total runoff (mm)	Runoff ratio (%)
1	2010/11/11 17:50	13:20	0.25	13.7	54.1	9.5	17.6
2	2010/11/12 20:20	2:20	0.34	3.2	9.6	0.3	3.6
3	2010/11/15 14:30	8:00	0.37	0.8	5.3	0.0	0.7
4	2010/11/24 19:50	1:10	0.31	1.9	6.3	0.2	2.5
5	2010/12/7 21:00	5:40	0.30	2.2	5.6	0.3	5.8
6	2010/12/12 20:00	8:50	0.34	1.9	11.0	0.5	5.0
7	2010/12/21 9:30	12:00	0.33	3.2	18.0	1.1	6.3
8	2011/1/7 2:50	10:10	0.50	3.8	30.5	1.9	6.2
9	2011/1/8 14:00	4:00	0.51	8.2	47.4	3.7	7.7
10	2011/1/10 14:00	1:30	0.50	5.3	20.8	4.5	21.6
11	2011/1/13 14:50	5:30	0.51	4.8	20.4	5.3	26.1
12	2011/1/14 12:40	5:40	0.53	5.8	12.1	4.0	33.1
13	2011/2/7 11:00	1:50	0.28	11.0	38.5	1.0	2.6
14	2011/2/8 12:50	1:10	0.42	7.5	14.4	0.5	3.4
15	2011/2/9 11:00	5:00	0.44	5.8	8.9	1.4	15.6
16	2011/2/12 10:10	7:00	0.44	4.4	5.6	1.8	32.4
17	2011/2/13 8:30	6:50	0.45	3.1	15.4	8.3	53.6
18	2011/2/17 12:40	4:10	0.41	4.9	18.7	4.2	22.3
19	2011/2/19 13:20	9:00	0.44	1.7	8.5	2.4	28.4
20	2011/3/1 15:10	0:30	0.35	3.7	6.1	0.5	8.0
21	2011/3/3 12:40	0:40	0.38	2.9	5.7	0.4	6.4
22	2011/3/4 12:40	2:10	0.40	6.5	16.9	0.1	0.7
23	2011/3/5 21:30	15:50	0.45	2.2	17.3	0.0	0.2
24	2011/3/7 19:50	12:40	0.46	0.9	8.7	0.0	0.4
25	2011/3/14 13:00	10:10	0.37	8.4	12.8	3.0	23.2
26	2011/3/15 12:20	12:40	0.42	9.7	40.3	0.9	2.3
27	2011/3/16 11:20	27:30	0.50	4.0	26.6	0.3	1.0
28	2011/3/18 13:00	27:50	0.49	8.0	44.7	2.4	5.3
29	2011/3/20 11:40	11:00	0.49	4.6	27.6	5.6	20.2
30	2011/3/23 0:20	8:40	0.47	4.2	12.3	4.1	33.2
31	2011/3/24 18:40	1:00	0.47	4.6	10.1	5.7	56.3
32	2011/3/26 13:20	3:30	0.47	3.0	9.0	3.8	41.9
33	2011/3/27 13:20	1:50	0.49	3.0	5.7	3.2	56.4
34	2011/3/28 13:20	2:20	0.48	5.9	13.3	7.6	57.2
35	2011/3/31 11:20	12:40	0.48	7.1	42.1	15.2	36.1
36	2011/4/1 11:20	17:10	0.51	2.4	12.8	7.1	55.2
37	2011/4/3 14:00	6:40	0.49	4.8	11.8	8.0	67.7
38	2011/4/4 14:10	6:10	0.50	6.0	31.9	18.2	57.0
39	2011/4/5 14:50	9:10	0.50	2.8	11.4	6.4	55.8
40	2011/4/6 11:50	30:50	0.51	3.8	28.3	3.9	13.9
41	2011/4/8 14:40	25:30	0.51	1.9	11.5	2.0	17.4
42	2011/4/18 13:40	2:20	0.51	5.4	10.4	4.5	43.4
43	2011/4/18 22:30	133:10	0.53	1.2	32.3	3.3	10.4
	Total				800.7	157.2	
	Average	11:30	0.44	4.7	18.6		
	Max.	133:10	0.53	13.7	54.1		
	Min.	0:30	0.25	0.8	5.3		

Table S2. Summary of rainfall and runoff for each rainfall event at TA.

Event number	Date	Duration	Initial soil water content in 0-15 cm depth (m^3 m^{-3})	Max rainfall intensity (mm 10 min.$^{-1}$)	Total rainfall (mm)	Total runoff (mm)	Runoff ratio (%)
1	2010/11/12 15:30	8:00	0.16	6.9	22.7	0.0	0.2
2	2010/11/15 19:00	1:50	0.22	4.0	8.6	0.5	5.7
3	2010/11/16 15:30	4:20	0.23	2.1	5.2	0.0	0.0
4	2010/12/6 20:50	10:10	0.17	5.3	13.8	0.0	0.2
5	2010/12/8 1:40	17:10	0.19	2.3	16.6	0.0	0.0
6	2010/12/9 21:50	18:50	0.26	4.4	28.1	1.4	5.0
7	2010/12/21 16:50	4:30	0.23	12.0	44.4	2.6	5.8
8	2010/12/25 21:00	7:10	0.29	5.7	11.1	1.5	13.6
9	2010/12/29 18:40	9:10	0.29	3.8	10.5	0.5	4.9
10	2011/1/6 22:20	13:30	0.23	8.4	70.6	3.8	5.4
11	2011/1/8 14:30	13:30	0.34	9.2	19.5	1.4	7.0
12	2011/1/10 14:40	1:00	0.33	11.5	20.9	0.6	3.0
13	2011/1/12 0:30	5:30	0.34	9.2	59.2	2.5	4.2
14	2011/1/13 9:20	8:00	0.36	9.0	19.7	0.4	1.8
15	2011/1/14 19:20	5:20	0.35	11.3	49.9	1.6	3.3
16	2011/2/12 8:50	7:40	0.17	7.4	40.4	2.0	4.9
17	2011/2/13 7:50	5:00	0.35	6.4	28.8	2.1	7.4
18	2011/2/15 12:20	3:20	0.33	5.6	10.9	0.5	4.7
19	2011/2/19 16:50	12:50	0.31	6.4	31.6	1.4	4.4
20	2011/3/3 16:10	3:00	0.19	1.0	5.8	0.0	0.0
21	2011/3/5 10:50	20:00	0.19	11.4	59.6	1.9	3.2
22	2011/3/7 18:30	11:40	0.32	11.2	37.6	0.7	1.8
23	2011/3/14 18:20	36:10	0.23	9.2	123.8	3.0	2.5
24	2011/3/16 21:40	18:10	0.34	12.1	47.0	0.9	1.9
25	2011/3/18 12:40	11:30	0.34	2.4	5.0	0.0	0.0
26	2011/3/19 18:10	27:50	0.32	11.5	85.5	0.7	0.8
27	2011/3/21 12:30	10:20	0.36	12.4	42.4	15.5	36.5
28	2011/3/23 3:50	5:20	0.35	4.6	26.3	2.9	10.9
29	2011/3/25 23:00	2:00	0.30	2.3	6.2	0.0	0.0
30	2011/3/26 18:30	8:30	0.30	4.4	12.8	2.0	16.0
31	2011/3/29 3:40	30:10	0.30	5.2	18.9	1.1	5.8
32	2011/3/31 16:30	11:00	0.32	8.0	52.0	18.1	34.9
33	2011/4/2 21:00	22:10	0.32	7.1	11.6	3.3	28.0
34	2011/4/4 17:50	2:30	0.32	12.4	35.3	12.6	35.6
35	2011/4/5 17:00	49:00	0.35	4.8	43.5	7.7	17.7
36	2011/4/11 16:40	20:30	0.31	6.0	37.2	14.5	38.9
37	2011/4/13 2:20	5:40	0.38	4.0	14.3	3.4	24.1
38	2011/4/13 18:10	8:40	0.38	1.7	10.1	0.0	0.3
39	2011/4/17 19:20	6:40	0.33	2.1	9.2	3.5	38.1
40	2011/4/19 4:40	56:50	0.36	5.1	87.9	35.4	40.3
41	2011/4/22 5:00	52:40	0.38	3.6	54.0	18.7	34.6
42	2011/4/25 22:30	4:50	0.34	2.7	9.9	2.1	20.7
43	2011/4/28 0:00	3:00	0.37	4.4	15.4	9.6	62.5
	Total				1363.8	180.5	
	Average	13:36	0.30	6.5	31.7		
	Max.	56:50	0.38	12.4	123.8		
	Min.	1:00	0.16	1.0	5.0		

Table S3. Summary of rainfall and runoff for each rainfall event at SO.

Event number	Date	Duration	Initial soil water content in 0-15 cm depth (m^3 m^{-3})	Max rainfall intensity (mm 10 min.$^{-1}$)	Total rainfall (mm)	Total runoff (mm)	Runoff ratio (%)
1	2010/12/8 0:50	17:20	0.06	8.4	48.5	4.7	9.7
2	2010/12/10 0:50	6:00	0.20	2.0	8.5	0.1	1.0
3	2010/12/27 20:00	10:00	0.14	10.6	55.9	1.1	2.0
4	2011/1/7 3:30	8:40	0.11	4.3	36.8	2.2	6.1
5	2011/1/14 20:30	3:30	0.17	3.6	5.2	0.1	1.6
6	2011/2/12 12:40	4:00	0.12	4.7	11.0	0.9	8.3
7	2011/2/13 7:10	5:30	0.13	8.0	27.8	0.8	2.9
8	2011/2/17 13:00	4:10	0.17	7.8	22.1	0.8	3.4
9	2011/2/19 19:20	11:10	0.18	2.6	15.5	0.8	5.0
10	2011/3/5 20:20	9:40	0.14	12.7	50.5	2.3	4.6
11	2011/3/18 22:20	2:40	0.15	2.7	7.3	0.5	6.2
12	2011/3/19 18:50	7:10	0.18	2.0	11.9	0.2	1.5
13	2011/3/23 5:30	4:10	0.18	3.7	17.9	8.2	45.6
14	2011/3/29 15:40	1:00	0.18	7.8	17.0	5.2	30.5
15	2011/3/31 22:20	15:50	0.18	2.7	13.1	2.0	14.9
16	2011/4/3 15:40	3:00	0.20	4.4	11.4	3.4	29.7
17	2011/4/4 16:00	4:20	0.20	1.5	5.9	0.1	1.7
18	2011/4/6 13:00	16:10	0.21	3.8	17.0	11.6	68.1
19	2011/4/8 14:00	3:50	0.21	2.7	6.4	1.8	27.9
20	2011/4/16 20:10	4:20	0.20	3.2	16.9	7.7	45.4
21	2011/4/17 19:50	4:50	0.21	3.5	8.0	2.6	32.9
22	2011/4/19 1:40	37:50	0.21	3.4	45.5	18.4	40.4
23	2011/4/22 4:40	31:40	0.21	3.2	29.9	14.3	47.9
	Total				490.0	89.5	
	Average	9:25	0.17	4.8	21.3		
	Max.	37:50	0.21	12.7	55.9		
	Min.	1:00	0.06	1.5	5.2		

Table S4. Summary of rainfall and runoff for each rainfall event at MA.

Event number	Date	Duration	Initial soil water content in 0-15 cm depth ($m^3\ m^{-3}$)	Max rainfall intensity (mm 10 min.$^{-1}$)	Total rainfall (mm)	Total runoff (mm)	Runoff ratio (%)
1	2010/12/8 1:00	19:30	0.04	2.8	18.9	0.6	3.1
2	2010/12/10 2:50	12:40	0.11	2.2	5.1	0.0	0.6
3	2010/12/21 15:40	6:40	0.03	6.0	17.1	0.2	1.1
4	2010/12/27 21:50	4:50	0.07	8.9	33.9	0.5	1.5
5	2011/1/7 3:40	8:20	0.06	2.9	34.7	0.0	0.0
6	2011/1/8 15:40	12:20	0.12	4.3	12.8	0.5	3.5
7	2011/1/12 17:20	17:40	0.09	3.6	8.2	0.1	1.6
8	2011/2/12 8:30	8:10	0.04	12.0	34.8	0.3	0.9
9	2011/2/13 6:50	6:20	0.14	3.1	15.1	0.0	0.0
10	2011/2/17 12:50	4:10	0.09	7.8	24.9	0.0	0.1
11	2011/2/18 20:20	10:30	0.11	9.8	26.6	0.0	0.1
12	2011/2/19 18:50	10:40	0.13	9.6	14.6	0.0	0.2
13	2011/3/5 10:50	21:30	0.03	5.3	28.1	0.6	2.2
14	2011/3/23 6:30	3:10	0.09	5.0	33.8	1.7	5.1
15	2011/4/3 15:10	12:40	0.08	5.1	15.9	21.7	136.6
16	2011/4/5 15:40	5:40	0.09	1.4	6.5	0.0	0.0
17	2011/4/6 13:30	0:50	0.10	3.0	5.3	1.4	25.6
18	2011/4/7 3:00	12:30	0.11	4.4	8.8	4.8	54.0
19	2011/4/8 15:10	2:50	0.09	6.3	9.6	6.0	62.0
20	2011/4/11 22:50	15:10	0.07	6.2	11.5	6.0	51.8
21	2011/4/13 7:40	6:10	0.10	3.3	11.2	5.1	45.9
22	2011/4/19 4:40	38:30	0.07	1.8	16.3	1.1	6.9
23	2011/4/21 12:00	2:40	0.10	4.5	13.5	9.5	70.5
24	2011/4/22 6:40	29:50	0.11	1.9	15.3	1.6	10.1
25	2011/4/29 16:00	0:50	0.06	5.0	6.7	1.0	15.0
	Total				429.2	62.7	
	Average	10:58	0.08	5.0	17.2		
	Max.	38:30	0.14	12.0	34.8		
	Min.	0:50	0.03	1.4	5.1		

APPENDIX II
JAPANESE ABSTRACT

タンザニア・モロゴロ州の畑作地における最適な農業管理による養水分利用効率の改善

西垣智弘

第 1 章 序論

半乾燥熱帯に位置するタンザニア・モロゴロ州は、ウルグル山塊を中心として多様な土壌・気候条件の下で多様な農業体系が分布しており、多くの農民は天水と最小限の化学肥料に依存しながら農業を営んでいる。そのため、水食や溶脱による農地系外への養水分損失が生産性の低下を引き起こしており、養水分利用効率の改善のための農業管理技術の確立が求められている。しかしながら、当地域における水食特性の評価、表面流去水と土壌損失の発生メカニズムに基づく適切な土地管理の検討は十分になされていない。また、同一の農業管理を適用した際の土壌中の養水分動態の変化は、土壌型ごとに異なると考えられる。したがって、養水分利用効率を改善するための最適な農業管理を土壌型ごとに明らかにするためには、作物栽培期間中の土壌－作物間の養水分動態を定量的に評価する必要がある。以上の背景を踏まえ、本研究ではタンザニア・モロゴロ州の畑作地における生産性向上のために、当地域の多様な環境条件下における養水分動態の定量的な解析と、その結果に基づく最適な農業管理による農地系外への養水分損失の抑制と、作物の養水分利用効率の改善を目的とした。

第 2 章 研究対象地の概要

本研究は、タンザニア・モロゴロ州において行った。ウルグル山塊周辺の土壌・気象条件の異なる 4 地点（NY、TA、SO、MA）を調査対象地として設定し、全 4 地点において水食特性の評価を行い、SO（粘土質圃場）と MA（砂質圃場）においてトウモロコシ栽培試験を行った。水食特性評価試験は、小雨季と大雨季（2010 年 11 月—2011 年 5 月、計 160 日間）に行い、各地点において表面流去プロット（幅 0.8 m×斜面長 2.0 m）を 2 連で設置し、裸地状態で、表面流去水量、降雨量、土壌体積含水率を 10 分間隔で測定し、流亡土砂を約 2 週間に 1 度回収し、計量した。栽培試験は 2012 年と 2013 年の大雨季（3-6 月）に行い、処理区として作物残渣無施用区（Ctrl 区）、化学肥料施用区（F 区）、トウモロコシ残渣すきこみ区（M-In 区、C:N 比 = 60）、トウモロコシ残渣表面散布区（M-On 区）、ササゲ残渣すきこみ区（P-In 区、C:N 比 = 21）の計 5 処理区を設置した。試験期間中、表層土壌（0-30 cm）中の無機態窒素量（NO_3^{-}-N、

NH_4^+-N)、地上部トウモロコシ中の窒素吸収量、土壌呼吸速度を定期的に測定し、降水量、土壌水分量も継時的に測定した。

第 3 章 モロゴロ・ウルグル山塊の異なる土壌・降雨条件下における表面流去水発生と土壌損失

モロゴロ州ウルグル山塊における土壌・降雨条件が異なる 4 サイト(NY、TA、SO、MA)における水食特性を評価した。西側斜面高標高に位置する NY では、クラストの形成が確認され、表層の飽和透水係数が非常に低く、流出率が高かった。また、雨季後半には表層から 60 cm 深までほぼ飽和に達した。東側斜面の TA は降雨量が最も多く、強い降雨強度を伴った降雨の割合も高かった。表層の透水性は良好で流出率は抑えられたが、降雨量の多さゆえ流亡土砂量は最も多かった。斜度の緩い中粒質な SO では最も高い流出率が観測されたが、土砂濃度は最も低く、クラストの形成が観察された。高い強度を伴う降雨の割合が雨季前半に高いため、この時期の流亡土砂量も多かった。MA は流出率が低く傾斜が緩やかであるにもかかわらず、その砂質土壌ゆえの流亡耐性の低さから、土砂濃度が最も高かった。水食抑制には、表層土壌の浸透能を維持し、表面流去水の発生とそれに伴う土砂流亡を抑制することが重要であることから、多様な環境条件に幅広く適用可能な水食抑制技術として、マルチによる地表面の保護が有効であると考えられた。

第 4 章 タンザニア・モロゴロ州の異なる土性を有する 2 圃場において作物残渣の質と施用方法が土壌呼吸量と土壌炭素蓄積量に与える影響

モロゴロ州の粘土質圃場と砂質圃場の 2 地点において、トウモロコシ残渣のすきこみ区(M-In 区)、表面散布区(M-On 区)、ササゲ残渣のすきこみ区(P-In 区)、化学肥料区(F 区)、残渣無施用区(Ctrl 区)の 5 処理区を作成し、定期的に測定した土壌呼吸速度から 2 年間の土壌呼吸量を推定した。また、試験期間中の土壌炭素蓄積量の変化も調べた。試験期間は例年に比べて少雨であり、土壌呼吸量は抑制されたため、トウモロコシ残渣施用区では、施用法・土性を問わず積算土壌呼吸量よりも残渣による炭素投入量が大きくなり、土壌炭素蓄積量は増加することが示唆された。しかし、土壌炭素蓄積量はサンプリングに伴う空間的誤差が大きく、作物残渣の質および施用法の違いによる有意な変化はみられなかった。2 年間の土壌呼吸量は、粘土質圃場では M-In 区のほうが M-On 区よりも 39%高かったが、砂質圃場では M-On 区のほうが M-In 区よりも 17%高かった。砂質圃場では M-On 区において土壌水分含量が他の処理区に比べて高かったことから、土壌有機物の分解に伴う土壌呼吸量の増加が示唆された。ササゲ残渣を施用した P-In 区では、その高い生分解性によってトウモロコシ残渣を施用した M-In 区の約 2 倍の分解率を示した。

第 5 章　タンザニア・モロゴロ州の異なる土性を有する 2 圃場において作物残渣の質と施用方法が表層土壌中の窒素動態に与える影響

モロゴロ州の土性が異なる 2 つのトウモロコシ畑（粘土質圃場・砂質圃場）において、作物残渣管理（質および施用方法）が作物栽培期間中の表層土壌中の窒素動態に与える影響を調べた。粘土質圃場と砂質圃場の両圃場において、高い生分解性を有するササゲ残渣は施用後 2 週間以内に速やかに分解され、土壌呼吸速度と表層土壌中の無機態窒素量が増加した。その結果、両圃場のササゲすき込み区（P-In 区）ではトウモロコシすき込み区（M-In 区）よりも、特に作物生育初期の窒素利用効率が高く、最終的な作物窒素吸収量も 18-73%高くなった。作物残渣の施用方法の違い（すき込み、表面散布）については、粘土質圃場では M-In 区でトウモロコシ表面散布区（M-On 区）よりも土壌呼吸量は増加したが、表層土壌中の無機態窒素量と最終的な作物窒素吸収量および収量に有意な差はなかった。一方、砂質圃場では、M-On 区で M-In 区よりも栽培期間中の土壌水分量が高く維持されたため、表層土壌中の平均無機態窒素量は 18-26%増加し、最終的な作物窒素吸収量が 26-59%増加した。

第 6 章　要約および結論

タンザニア・モロゴロ州の畑作地における養水分動態は土壌型や気象条件に伴って大きく異なることが多地点の現場圃場試験によって示された。山間地域における高い降雨量や、砂質土壌の高い受食性が水食リスクを高める要因であることを明らかにし、モロゴロ州における多様な土壌・気象条件下において幅広く適用可能な水食抑制技術として、表層土壌の浸透能を維持し、土壌の流亡耐性を向上する地表面のマルチ（表面被覆）を提案した。また、作物残渣の施用は、2 年間の圃場試験では土壌有機物蓄積量を顕著に増加しなかった一方で、作物生育期間中には土壌型に応じて養水分利用効率を改善することが示された。粘土質圃場では、施用したトウモロコシ残渣の分解はすき込みのほうが表面散布よりも促進されるが、作物の養水分利用効率に影響は与えないことを明らかにした。一方、保水性の低い砂質圃場ではトウモロコシ残渣の表面散布はすき込みと比べて土壌水分状態を高く維持し、その結果、土壌有機物の無機化が促進され、表層土壌中の無機態窒素量が増加し、作物による窒素利用効率を向上することを明らかにした。生分解性の高いササゲ残渣は、土壌型によらず、施用後速やかに分解され、特に作物生育初期の表層土壌中の無機態窒素量と、作物の窒素利用効率を向上することを明らかにした。以上より、作物残渣や休閑植生残渣などの有機物資材を用いた農業管理を、土壌・気象条件に応じて単一的にあるいは複合的に導入することで、タンザニア・モロゴロ州の多様な土壌・気象条件下の畑作地における養水分利用効率は改善することができる。

PUBLICATION

Chapter 3

Nishigaki T, Sugihara S, Kilasara M, Funakawa S, 2017. Surface runoff generation and soil loss under different soil and rainfall properties in the Uluguru Mountains, Tanzania. *Land Degradation and Development*, John Wiley & Sons, Ltd., 28, pp283–293. DOI: 10.1002/ldr.2499

Chapter 4

Nishigaki T, Sugihara S, Kilasara M, Funakawa S, Soil CO_2 flux and soil carbon stock under different quality and application methods of crop residues in maize croplands with contrasting soil textures in Tanzania. (in preparation for submitting to *Nutrient Cycling in Agroecosystems*)

Chapter 5

Nishigaki T, Sugihara S, Kilasara M, Funakawa S, 2017. Soil nitrogen dynamics under different quality and application methods of crop residues in maize croplands with contrasting soil textures in Tanzania. *Soil Science and Plant Nutrition*, Taylor & Francis, 63, pp288－299. DOI: 10.1080/00380768.2017.1332454