Agro-ecological study on Chagga home garden system in Kilimanjaro highlands

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Chapter 1
Introduction

1.1. Study background

Smallholder farming systems are characterized by small farmland size (< 2 ha), reliance on family labor, low external input, and low-yield agriculture using local resources (FAO, 2015). The smallholder farming system in sub-Saharan Africa (SSA) is further characterized by its diversity. It takes place under a wide range of soil, climatic, and socio-economic conditions, and it is strongly constrained by the limited availability of key resources such as land, plant nutrients, cash, and labor (Giller et al., 2006). Smallholder farmers developed diverse farming systems by traditional judicious management practice of their farmland, using resources available in their vicinity and adopting agricultural practices geared towards improved soil fertility in fallow, agroforestry, green manuring, and crop-livestock system (e.g., Fan and Rue, 2020; Tsujimoto et al., 2019; Vanlauwe et al., 2014). Agriculture accounts for about 35% of GDP and 60% of employment in SSA, and 90% of agricultural production in SSA is supplied by smallholder farmers (OECD-FAO, 2016). There is a growing demand for food from the burgeoning population in SSA, which will be approximate twice the current population by 2050 (UN, 2019). Therefore, the smallholder farming system plays a crucial role in sustaining food production and employment generation in SSA (Mesfin et al., 2020).

The United Republic of Tanzania (Tanzania), located in East Africa, has a large increase in population. The population growth rate ranks 13th in the world (UN, 2019). Approximately 70% of the total population of the country lives in rural areas and about 80% of them are engaged in the smallholder farming. Therefore, sustainable development of smallholder farming system is essential for ensuring a stable food supply and employment in Tanzania. The southeastern slopes of Mount Kilimanjaro in northeastern Tanzania are one of the most densely populated areas in the country. The population density of the southeastern slopes was 810 to 1,200 people km^{-2} in 2012, considerably higher than the national average, which was 51 people km^{-2} (The United Republic of Tanzania, 2012). The Kilimanjaro region is known for its agricultural activities. The yield of banana and coffee rank second and fourth, respectively, among the 31 states of Tanzania, and the share of bananas in the Kilimanjaro region accounts for 17% of the domestic market (The United Republic of Tanzania, 2020). The high agricultural production in the Kilimanjaro region is supported by Andosols, which are ideal soils for agricultural production, as well as a cool climate and abundant rainfall (Fernandes et al., 1984; Soini 2005a; Hemp 2006; Zech et al., 2014). The soils in Tanzania are dominated by highly weathered clayey soils such as Acrisols, Alisols, Ferralsols, and Lixisols, while the Kilimanjaro highlands are dominated by Andosols and Nitisols (Jones et al., 2013). The Kilimanjaro highlands has high precipitation of 1,000–1,500 mm in contrast to the low precipitation ranging from 0–750 mm in the central and inland areas of the country. Thus, the Kilimanjaro highlands have a very favorable agro-ecosystem unlike many other regions in SSA where agricultural production is low due to poor soil fertility and drought by climate variability (Frelat et al. 2016).

At a high altitude of 1,000 to 1,800 m a.s.l. in the Kilimanjaro highlands, the smallholder farming system using a home garden system has been managed by the Chagga people (Fernandes et al., 1984). The home garden system is characterized by multipurpose trees and shrubs in intimate association with annual and perennial crops and livestock around the homestead, ensuring multiple products and income for farmers. Home garden systems are mainly found in the tropics and temperate zones and provide a stable food and income to local people using a small area less than 0.5 ha (Kumar and Nair 2004, 2006). The Chagga's home garden system is characterized by the combination and interdependence of crop production and livestock holding, namely crop-livestock system. The farmland provides feed, such as crop residues and grass, to the livestock, while the livestock provides manure to crop cultivation which is a main or only fertilizer applied in the home garden (Fernandes et al., 1984). The Chagga home garden system in the Kilimanjaro highlands is recognized as one of the most sustainable agricultural systems, as it has provided food and income to the local people for over 100 years through efficient resource recycling using livestock and agricultural land (Fernandes et al., 1984; FAO, 2011). Given the important role of this system in the local people and national level in terms of maintaining livelihood and stable food supply, the Chagga home garden system has been described in terms of the components of the system, the historical background of Chagga culture, or changes of the system from a social scientific perspective (Fernandes et al., 1984, 1986; Soini, 2005a,b; Bender, 2013). However, it is not well documented how agricultural productivity has been maintained for a long period.

Previous studies showed a quantitative evaluation of carbon (C) and nutrient flows of a farming system, and C and nutrient budgets in the farmland soil is a help to develop the sustainable land management of a smallholder farming system (Ebanyat et al., 2010; Kiboi et al., 2019; Nziguheba et al., 2021). Most studies in smallholder farming systems in SSA showed negative N, P, and K balances (Stoorvogel et al., 1993; Harris, 1998; Esilaba et al., 2005; Mesfin et al., 2020; Nziguheba et al., 2021; Rakotoson et al., 2022), which confirmed the nutrient depletion in farmland soil and suggested severe consequences for future food security. Previous studies also showed the agricultural productivity and land use of the smallholder farming systems in SSA are influenced by several factors. Changing socio-economic and environmental conditions often impact individual farms' land management strategies, and hence these changes influence the sustainability of the entire farm system (Tittoenell et al., 2007; Ebanyat et al., 2010; Mellisse et al., 2018). Previous studies showed that C and nutrient balance of smallholder farming systems under limited organic resources was strongly influenced by land management such as the number of cattle holding (Baijukya et al., 1998; Throne and Tanner, 2002), in addition to cultivating crop species, distance from homestead, frequency of tillage (Baijukya et al., 2005; Zingore et al., 2007; Moges and Holden, 2008; Goenster et al., 2014; Salim et al., 2017), and socio-economic conditions of household (Haileslassie et al., 2006; Tittonell et al., 2009; Mesfin et al., 2020). Based on these studies, I, therefore, hypothesize that farmland management strategies such as livestock holding and farmland management, as well as C and nutrient flows of the system, are important factors controlling the agricultural productivity of the Chagga home garden system.

1.2. Study Objectives

The objective of this study was to understand how the Chagga people have maintained their home garden system for more than 100 years in the Kilimanjaro highlands by using socio-economic approaches and nutrient-budget approaches. This study examined 1) understanding the relationship between agricultural practices and livelihood strategies of the Chagga people under the current socio-economic environment, 2) quantifying the effect of livestock holding and land management on soil fertility in the home garden, and 3) evaluating C and nutrient flow of the home garden system. The findings of this study about soil fertility management implemented by the Chagga people will be helpful for the sustainable development of the home garden system and thereby contribute to the food supply of the local people and Tanzania.

The thesis comprises the following chapters: In Chapter 2, the geological and agricultural conditions of the studied area are described. In Chapter 3, the adaptation of farmland management strategies to maintain livelihood by the Chagga people is discussed. In Chapter 4, the roles of livestock and land-use in soil fertility of the home gardens are discussed. In Chapter 5, C and nutrients budget of the home garden system are discussed. In Chapter 6, a general discussion is presented, and the main conclusions are summarized.

Chapter 2
General description of the study area

2.1. General of Tanzania

Tanzania is located in the eastern part of Africa, which possesses a complex landscape formed by the western and eastern branches of the East African Rift. The climate varies from tropical on the coast to temperate in the highlands (Luhunga et al., 2018). There are two predominant precipitation regimes with an average annual rainfall of 600–800 mm. In the northern and eastern parts of the country, there is a bi-modal precipitation regime with the long rains generally occurring between March and May and the short rains experienced from October to December. In the center and southern parts of the country, there is generally one rainy season from December to May (Basalirwa et al., 1998). Primary soil types are Acrisols, Alisols, Ferralsols, Lixisols, Nitisols, Plinthosols, and Vertisols, and others include Andosols, Cambisols, and Fluvisols (Jones et al., 2013). They have developed from many types of geological parent materials under various time scales and environmental conditions as affected by the East African Rift (Jones et al., 2013). The population is 59,734,213 people in 2020 (World Bank, 2020), and it is estimated that the population in Tanzania will grow to 129,387,000 by 2050 (UN, 2019). More than 120 ethnic groups constitute Tanzanian people, including Sukuma, Chagga, Nyamwezi, Makonde, Hehe, Haya, Nyakyusa, and others (Laurence, 2009). Each ethnic group speaks their local language and Swahili, the country's official languages; simultaneously, they preserve their cultural and ethnic identity.

The economy of Tanzania has a high dependence on agriculture, accounting for 28% of GDP and contributing 24% of annual export earnings (The United Republic of Tanzania, 2021). Most of the population in Tanzania engaged in agriculture are smallholder farmers. Crop production was the most common agricultural activity accounting for 65% of all agricultural households, followed by 33% engaged in crop and livestock, and 2% engaged in livestock only. Smallholder farmers grow a wide variety of annual and perennial crops such as paddy, maize, sorghum, bananas, beans, cowpeas, green gram, groundnuts, and sunflower. Cash crops, including cotton, tobacco, sisal, cashew nuts, coffee, and tea, are mainly grown by smallholders and large-scale commercial farmers for export (The United Republic of Tanzania, 2016; FAO, 2018).

2.2. Description of the Kilimanjaro highlands and the Chagga home garden system

Mount Kilimanjaro, which is the world’s highest free-standing mountain (5,895 m above sea level (m. a. s. l.)), is located in the Kilimanjaro region in the northeastern part of Tanzania between 2°45′ and 3°25′S and 37°0′ and 37° 43′E. Mt. Kilimanjaro is situated under a seasonally dry tropical climate (Hemp, 2006). However, rainfall and temperature vary with altitude and exposure to the dominant wind from the Indian Ocean. The southern slopes receive much more annual rainfall than the northern slopes. The southern slopes at 700 m a.s.l. receive an annual rainfall of 800–900 mm and slopes at 1,500 m a.s.l. receive 1,500–2,000 mm. The forest belt lies between 2,000 and 2,300 m a.s.l receive partly over 3000 mm. The rainfall pattern is seasonal, the long rainy season is from April to May, and the short rainy season is around November (Hemp, 2006). Mean annual temperature varies with altitude; at the foothills in Moshi town is 23.4°C and at the top of Kibo is −7.1°C. The soil type was classified as Andosols (Zech, 2014; Hemp, 2006). Mt. Kilimanjaro has a high diversity of ecosystems and vegetation due to the diverse climatic differences from lowland savannah to upper icecap. A dry and hot savanna zone surrounds the mountain base between 700 and 1000 m a.s.l., which is dominated by farmland, while the submontane and lower montane zone between 1000 and 1800 m has been converted to banana–coffee home gardens (Hemp, 2009). The diversity of its nature is exceptional, and to conserve this ecosystem, Mt. Kilimanjaro was classified as a natural reserve in 1921, a National Park in 1973, and a World Heritage Site by UNESCO in 1989.

The people who settled in the Kilimanjaro area are called the Chagga people (Picture 2.1). The Chagga descended from immigrants of various tribes, such as Wataita, Wakamba, Wapare, and Wamasai, who migrated into this area at least five or six hundred years ago (Fernandes et al., 1984). The Chagga people are well known for the ecological and economic success of their farming system. The percentage of literacy level of household members in the Kilimanjaro region was above 90%, which is the third-highest level for all regions in Tanzania (The United Republic of Tanzania, 2020). The agriculture of the Chagga people was started when they converted the native forest into farmland and began the process of cultivating yams, bananas, finger millet, and other crops in small home gardens in the Kilimanjaro highlands. Today, the Chagga's home garden system is characterized by the combination and interdependence of crop production and livestock holding. The crop production has been conducted in the farmland of the home garden. The farmland consists of the banana (*Musa spp.*) - coffee (C*offea arabica*) cultivation area with yam (*Dioscorea spp.*) and other small vegetables, and the maize (*Zea mays*) cultivation area with a small amount of beans (*Phaseolus vulgaris*), and the grassland (Soini, 2005a, b). The common livestock kept in the home garden was cattle and goats by stall-shed (Picture 2.2). Although livestock was a vital saving property and had an integral part of the Chagga's traditional events, the primary purpose of livestock holding was obtaining manure in this area (Soini, 2005b). The farmland provides feed, such as crop residues and grass, to the livestock, while the livestock provides manure to crop cultivation which was the main or only fertilizer applied in the home garden (Fernandes et al., 1984). This efficient cycling of diverse organic matter within the system was certified as a globally important agricultural heritage system (FAO, 2011).

2.3. Description of the study village

The study village (Makami-Chini village) was located in a part of the Kilema Kaskazini ward that consists of four villages on the southern slopes at 1,600 m.a.s.l. of Mt. Kilimanjaro (3°16′56″S, 37°28′49″E) (Fig. 2.1). The rainy season was usually bimodal with the long rainy season (April and May) and the short rainy season (around November). The mean annual rainfall was 1,571 mm, and the mean annual temperature of 21.0°C in 2017/2018 (Fig. 2.2). The primary soil type was classified as Andosols (Zech, 2006) (Picture 2.3). The population of the Kilema Kaskazini ward was 9,149 in 2002 and 9,669 in 2012 (The United Republic of Tanzania, 2013). The study village consisted of 307 households containing 1,343 people (642 males and 701 females) in the 2012 census (Kilema Kaskazini village office, 2012). The cultivation area for each crop was 90 ha for bananas, 166 ha for coffee, 35 ha for maize, and 15 ha for beans in the 2012 census (Kilema Kaskazini village office, 2012).

2.4. Description of farmland management of the home garden in the study village

Typical home gardens in the study village included houses, farmland, and livestock sheds, with a hedge surrounding the property (Fig. 2.3). The farmland was managed differently for each crop cultivated, with traditional banana-coffee gardens generally occupying the majority of the farmland area closest to the houses, followed by field growing annual crops, mainly maize, and grassland (mainly elephant grass (*Pennisetum purpureum*)) for forage and these three blocks of the farmland are adjacent to each other. Traditionally, home gardens have been passed down from grandfather and managed for more than 60 years in the study village.

2.5. Description of livestock holding of the home garden in the study village

Cattle, goats, and sheep were traditionally kept as livestock, and some farmers have started keeping pigs. Cattle and goats have been kept for the purpose of obtaining manure, in addition to the role as assets, food, social status, and cultural activity in tradition, while pigs for cash income today. The average number of cattle, goats, and sheep was 1.4, 3.2, and 0.6, respectively (Table 2.1). In this study, all livestock were converted into tropical livestock units (TLU) since the number and type of livestock varied among households (Jahnke 1982). Before conversion to TLU, the cattle weight of each household was estimated by their height (compared to the height of mature cattle with 140-cm height), referring to the previous report in which the cattle body weight was highly correlated to their body height (Francis et al. 2002). Livestock density was defined as TLU per each household home garden size, which was measured using a GPS (Dakota 20, Garmin, USA). In this study, livestock density was used as an index for livestock holding in each household.

Table 2.1 Current situation of livestock holding in the study village.

	Quantity
Averaged number of cattle (min-max)	1.4 (0-7)
Averaged number of goats (min-max)	3.2 (0-13)
Averaged number of sheep (min-max)	0.6 (0-6)
Averaged TLU[a]	1.4 (0-4.9)
Averaged livestock density[b] (TLU ha^{-1})	4.4 (0-15.3)

[a] TLU (tropical livestock unit) is a unit for quantifying a range of different livestock types: 1 TLU = 250 kg of cattle live weight (Jahnke 1982).

[b] Average livestock density was defined as the average TLU per the average home garden size for banana cultivation of 32 households (0.31 ha). Home garden sizes for banana cultivation of 32 households were measured by GPS (Dakota 20, Garmin, USA) in November 2017.

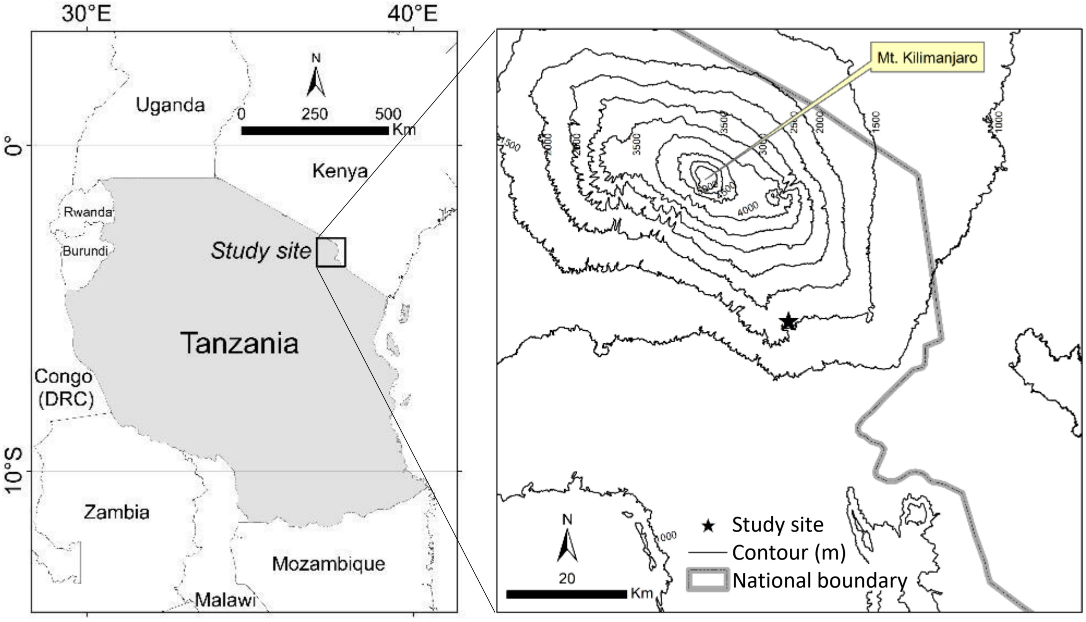

Fig. 2.1 Location of the study site.

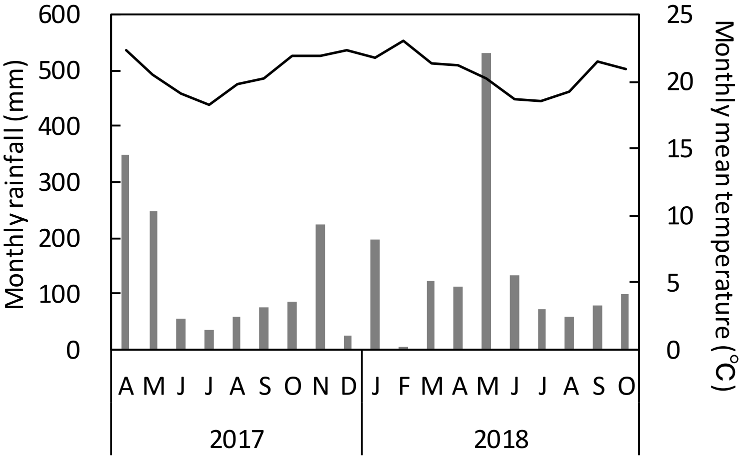

Fig. 2.2 Rainfall and monthly mean temperature of the study site in 2017/2018.

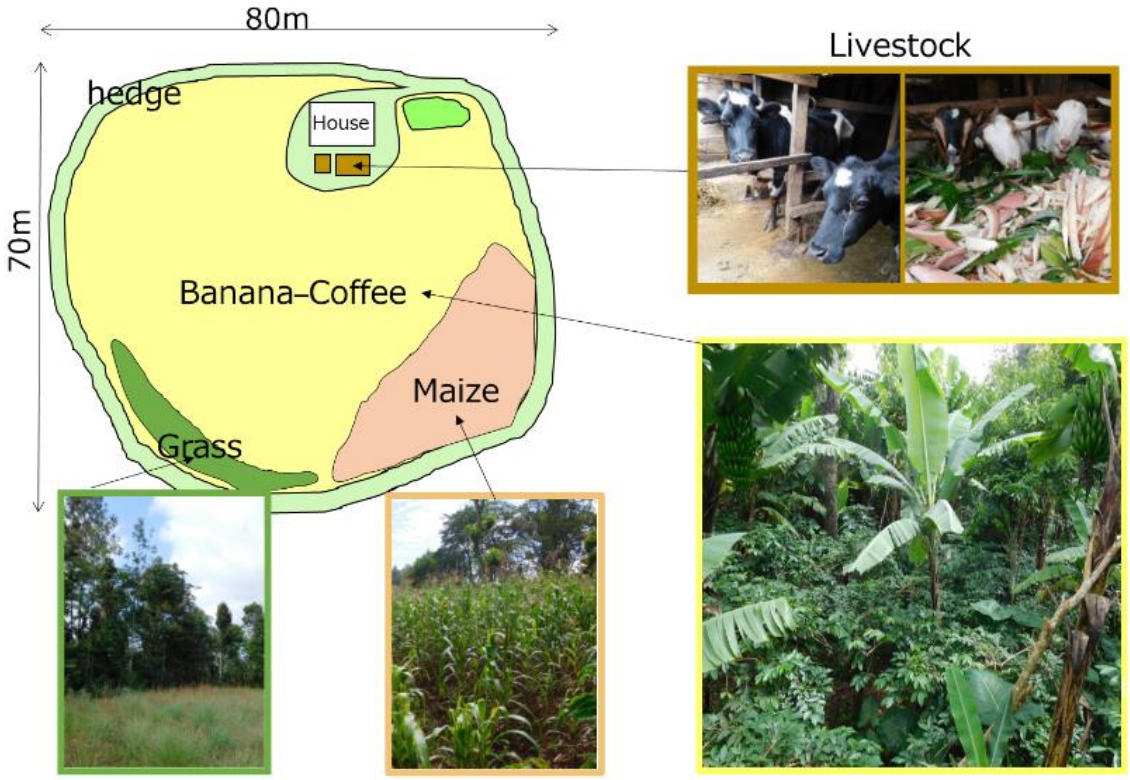

Fig. 2.3 General components of the traditional home garden in the study village.

Picture 2.1 The Chagga people in the study village.

Picture 2.2 Livestock and livestock sheds in the study village.

Picture 2.3 Soil profile in the study village.

Chapter 3

Adaptation of farmland management strategies to maintain livelihood by the Chagga People in the Kilimanjaro highlands

3.1. General

Agriculture is one of the key means of smallholder farmers' livelihood, which is defined on the basis of capabilities, assets, and activities required for a means of living (DFID, 2001). To secure the sustainability of their livelihood, smallholder farmers constantly change their farmland management by adopting multiple strategies—they expand, intensify, and diversify their agricultural systems to secure livelihood against external factors such as population increase, global market forces, climatic change, declining soil fertility, disease, and consumer demands (Altieri et al., 2012; Tittonell and Giller, 2013; Loison, 2015; OECD/FAO, 2016). Implemented farmland management is highly diverse because of specific agricultural conditions and livelihoods in different ecosystems and regions (Tittonell et al., 2010). This heterogeneity of interaction between farmland management and people's livelihood makes it difficult to fully understand the impacts of contemporary socio-economic and environmental changes on small-scale farming systems, which are the basis of sustainable livelihood for smallholder farmers.

The selection of crops to cultivate in the small-scale farming system depends on smallholder farmers' knowledge, incentives, and preferences (Tittonell et al., 2010; Assefa and Hans-Rudolf, 2016; Shikuku et al., 2017), as well as on dietary, cultural, and marketing considerations (Bellon, 2009; Andersen, 2012; Johns et al., 2013). The composition of species and genotypes of crops in farmlands affect the functional responses to external stressors. Increasing crop diversity is one of the farmland management strategies that can increase the redundancy of small-scale farming systems and contribute to maintaining the food security and economic benefits of smallholder farmers (Di Falco and Perrings, 2003; Lin, 2011; Félix et al., 2018; Mastretta-Yanes et al., 2018). Thus, it is important to study why and how smallholder farmers diversify specific species and genotypes of the crops in their farmlands. However, few studies have attempted to examine the adaptation strategy of smallholder farmers from this viewpoint.

In the small-scale farming system in the Kilimanjaro highlands, the farmland management of the Chagga people seemed to contribute to the sustainability of their farming system, however, several serious challenges have threatened their farming system and livelihood in the last decades (Soini, 2005b). The decrease in the size of home gardens with the rapid population growth in the Kilimanjaro highlands in the twentieth century is one of the major concerns for their livelihood security (Soini, 2005a, b). Additionally, prices of coffee fell in the 1960s, and prices of pesticides used for coffee production increased markedly in 1994 because of the liberalization of the Tanzanian coffee market. Afterward, global coffee prices collapsed from 1997 to 2005 (Winter-Nelson and Temu, 2002; International Coffee Organization, 2018). It is predicted that, through experiences from such external stress factors, the Chagga people have adopted multiple strategies to maintain their livelihood. However, how the Chagga people have altered their farmland management strategies to face these serious challenges is not well documented.

The current status of the main crop species cultivated in farmlands (banana, coffee, and maize) and the diverse genotypes of banana in home gardens should be a result of the strategy adopted by the Chagga people to adjust to the changes in socio-economic circumstances. The objective of this chapter was to examines the role of the main crop species and the diverse genotypes of banana in the livelihood of the Chagga people, to understand how they adapted their farmland management to maintain their livelihood by surveying (1) the farmland management in the present and the past, (2) the role of each crop cultivated as a staple food and income resource, and (3) the role of diverse genotypes of banana in daily life, using interviews, observation, and genetic analysis of bananas.

3.2. Materials and methods

3.2.1. Participant observation regarding general information about agricultural practices, livelihood, and banana varieties

Participant observation was used to decide the type of data needed to explain how they adapted their farmland management strategy to suit contemporary socio-economic changes. To understand the agricultural practices and the ways of livelihood in the village, I resided in the village for a total of one year: four months from June to September 2015; three months from November 2015 to January 2016; three months from April to June 2017; and two months from November to December 2017. Information on agricultural practices and livelihood in the past and traditional customs related to farmland management was collected from several key informants over 70 years of age, who were well versed in the history of the village. Additionally, to identify banana varieties cultivated in the study village, bananas were morphologically classified according to criteria provided by Simmonds (1966), Karamura et al. (2012), and Higuchi and Takata (2018). Then, information on local names, usage, taste, texture, characteristics of cultivation, and the market value of each banana variety was collected from several home garden owners and merchants at a local market. The cooking methods of the main staple food crops, banana, maize, and rice were also collected from several female villagers.

3.2.2. Semi-structured interviews regarding detailed information about the use of farmlands and crop species cultivated

On the basis of the participant observation data, a two-step survey using semi-structured interviews was conducted. The first step of the interview survey was conducted on 145 randomly selected households, which were evenly distributed across the village, between December 2015 and January 2016, to gather general information regarding farmland management in the study village. The owners of each household were interviewed by means of face-to-face interviews, using questionnaires in Swahili. The questionnaires asked about age, gender, and occupation of the owners, landholdings of farmlands, cultivated species of crops, the cultivated area of crops, and the current state of coffee cultivation.

The second step of the interview was conducted with 32 representative households by a stratified sampling method, based on my 145 households survey dataset, to carry out in-depth interviews between November and December 2017. Thirty-two households were randomly selected from 145 that represent three age groups of owners in the first step survey; four young households (19–40 years), ten middle-aged households (40–60 years), and 18 elderly households (above 60 years). The owners of each household were interviewed based on answers elicited by the questionnaires, which included information about changes of crop species after reduced or ceased coffee cultivation in home gardens, the farmland size inherited from owner's farther, the percentage of household consumption of staple food crops (banana, maize, and beans), and contribution to the household income of crop sales (banana, coffee, maize, and beans). Additionally, information about cultivated varieties and its planting density and shipment, as well as preference of each banana variety, was also collected. For household consumption, I divided the 32 households into two groups: households owning both home gardens and foothill farms (households with foothill farms, N = 22) and households owning only home gardens (households without, N = 10). This was done to evaluate the effects of landholdings on household consumption of each crop. For the data regarding household income generated by sales of each crop, the 32 households were divided again into two groups: households cultivating coffee (N = 21) and households that do not cultivate coffee (N = 11) to evaluate the effects of coffee sales on the income from crops. The home garden areas of the 32 households were measured using a GPS (Dakota 20, Garmin, USA) and calculated the foothill farm areas based on information provided by owners.

3.2.3. Assessment of daily diet

The 24-hour dietary recall method is commonly used to estimate individual or household levels of energy and nutrient adequacy, dietary quality, and diet composition, and this method requires a relatively minimal burden for respondents (FAO, 2018b). Ma et al. (2009) reported that three 24-hour dietary recalls were sufficient to estimate the energy intake. In this study, owners of 32 households of the second interview survey were interviewed about their meals, including breakfast, lunch, and dinner in the previous three days using 24-hours dietary recall method. The frequency rate of each staple food crop (banana, maize, rice, yam, wheat, and others) in the daily diet was calculated based on the responses from households.

3.2.4. Assessment of the diversity of bananas based on genetic analysis

Banana leaf samples were collected in May 2017 for genetic analysis, and DNA was extracted from dry leaf samples using the cetyltrimethylammonium bromide (CTAB) method (Doyle and Doyle, 1987). Afterward, DNA amplification was conducted through polymerase chain reaction, following Higuchi and Takata (2018) and using the Inter Simple Sequence Repeat (ISSR) primers UBC 807 to 868 (University of British Columbia, Canada), where ten primers (UBC 807, 808, 810, 815, 825, 834, 836, 840, 866, and 868) were selected and used to amplify the DNA samples. Furthermore, clear genetic polymorphisms from the band patterns obtained from the ISSR analysis was recorded. Additionally, a binary matrix was constructed on the basis of the presence (1) or absence (0) of a clear band. The poppr package (Kamvar et al., 2014; Kamvar et al., 2015) in R software (R Development Core Team, 2005) was used to calculate Nei's genetic distance (Nei, 1972). Nei's genetic diversity index was calculated on the basis of the genetic distance data matrix obtained using GenAlEx 6.5 (Peakall and Smouse, 2012), and a principal coordinate analysis (PCoA) was conducted.

3.2.5. Statistical analysis

To analyze the data collected from the second interview survey of the 32 households, Student's t-test was used to assess differences in (1) the percentages of household consumption of each harvested crop (bananas, maize, and beans) between households with foothill farms (N = 22) and households without (N = 10), and (2) the percentage of income generated by sales of each crop (bananas, coffee, maize, and beans) in households cultivating coffee (N = 21) and in households that do not (N = 11). In all cases, a p-value < 0.05 was considered significant. All statistical analyses were performed using SigmaPlot 11.0 (Systat Software, Inc., San Jose, CA, USA).

3.3. Results

3.3.1. Farmland management of home gardens and foothill farms

3.3.1.1. Cropping practice in home gardens and foothill farms

All 145 households interviewed in the first step interview survey were found to have been engaged in crop farming, and agriculture was the major occupation for 136 households (Table 3.1). According to several informants, the traditional farmlands owned by each household were constituted by home gardens and foothill farms in the past. However, 77 of 145 households owned both home gardens (located in the study village) and foothill farms (scattered in low-altitude areas around 900 to 1,000 m.a.s.l.), while the remaining 68 households owned only home gardens in this study (Table 3.1).

Maize was mainly cultivated in the study village until the nineteenth century, when coffee was introduced in this area. It was transferred to low-altitude areas under the instruction of the coffee extension services because of the scarcity of agricultural land for coffee cultivation in high-altitude areas. Thereby a traditional cropping practice, such as banana and coffee cultivation in home gardens and maize cultivation in foothill farms, was established in this area, according to several key informants. However, in this study, maize was cultivated in home gardens of all 145 households, though its cultivation area was smaller than for bananas (Table 3.1). Two types of households cultivated maize: those cultivating maize mainly in their foothill farms and partly at the edges of the home gardens, and those without foothill farms cultivating maize in the newly converted area for extensive maize cultivation in their home gardens (less than 40% of the home garden size). In the past, all households cultivated coffee in their home gardens by mixed cropping with bananas. However, of the 145 households, 99 reduced or ceased coffee cultivation in home gardens because of insect damage, low prices of coffee beans, and decrease in home garden size (Table 3.2). Of the 32 households in the second interview survey, 23 expanded banana and/or maize cultivation, instead

Table 3.1 Characteristics of 145 households in the study village.

Contents of questionnaire	Responses	
Age of owner (households)		
19<40	19	(13%)
40<60	45	(31%)
60<	81	(56%)
Gender of the owner (households)		
Male	109	(75%)
Female	36	(25%)
The main occupation of the owner (households)		
A farmer without off-farm activities	45	(31%)
A farmer with off-farm activities	91	(63%)
A farmer with a steady job[a]	9	(6%)
Landholding of farmlands (households)		
Home garden only	68	(47%)
Home garden and foothill farm	77	(53%)
Cultivated species of crops in the home garden (households)		
Banana	145	(100%)
Coffee	135	(93%)
Maize	145	(100%)
Beans	145	(100%)
Yam	145	(100%)
Cultivated species of crops in foothill farm[b] (households)		
Maize	77	(100%)
Beans	77	(100%)
Sunflower	28	(36%)
Cultivation area of banana and maize in the home garden (houseohlds)		
Banana > Maize	129	(89%)
Banana = Maize	16	(11%)
Banan < Maize	0	(0%)

[a] Steady job includeded tachers, nurses, priests, and business people.

[b] Responces from 77 households who owned foothill farms

of coffee cultivation, in the home gardens (Table 3.3). They expanded their banana cultivation because it can be used as an income source and staple food. In contrast, the motivation for expanding maize cultivation was only for obtaining staple food. This study found that the ownership of foothill farms declined, and the constitution of main crop species in home gardens altered. Several smallholder farmers expanded banana and maize cultivation instead of decreasing coffee cultivation in home gardens under limited farmlands.

3.3.1.2. Size of home gardens and foothill farms

According to the key informants, in Chagga society, home gardens are traditionally passed down from parents to their offspring. Their tradition dictates that the proportion of inheritance is determined by the number of male offspring and the birth order, as only males can inherit home gardens with the first-born and youngest siblings receiving the largest area. Conversely, other siblings

Table 3.2 Main factors influencing on the decision-making regarding coffee cultivation.

Main factors influencing decision-making	Number of households	
	(household)	(%)
Households that increased coffee cultivation (or stable [a])		
Cash income	26	
Good price of coffee	18	
Own enough homegarden size	2	
Total	46	32
Households which reduced or ceased coffee cultivation		
Insect damage	66	
The low price of coffee	17	
A decrease in the home garden size	12	
Labor shortage	3	
No market around the village	1	
Total	99	68
Ground total	145	100

[a] Including the households which did not increase, reduce , or cease coffee cultivation.

Table 3.3 Changes in crop species in home gardens after reduced or creased coffee cultivation and its purpose.

Change in crop type in the home gardens and its purpose	Number of houesholds
Households which reduced or ceased coffee cultivation	
Increased banana and maize cultivation	9
Increased only banana cultivation	6
Increased only maize cultivation	8
Increased vegetables	1
No change	1
Total	25
Households which increased banana cultivation [a]	
For daily diet	9
For income	6
Total	15
Households which increased maize cultivation [b]	
For daily diet	17
For income	0
Total	17

According to 25 households that reduced or ceased coffee cultivation of the 32 households in the second interview survey in December 2017.

[a] Including both households that increased banana and maize cultivation and increased only banana cultivation.

[b] Including both households that increased banana and maize cultivation and increased only maize cultivation.

only inherit small areas or cannot even inherit any farmland in recent times. Informant A, who was a first-born 54-year-old male with four sisters, inherited all of his father's home garden. Meanwhile, informant B, who was a first-born 75-year-old male with three brothers, inherited 50% of his father's home garden. His youngest brother inherited 40%, while his second and third brothers inherited 10% and 0%, respectively. Consequently, the second and third brothers had to leave the village to get jobs in urban areas. Additionally, informant C, who was a 56-year-old male and the youngest sibling with two brothers and five sisters, inherited 50% of his father's home garden, while his eldest brother inherited the other 50%. The other siblings did not inherit any farmlands, and consequently they left the village.

The average size of the home garden of the 32 households in the second interview survey was 0.31 ha. The owners of 24 of the 32 households inherited smaller portions of their fathers' home gardens, most of which were less than half of the areas that their fathers owned (Table 3.4). The other two households made new home gardens because they could not inherit them. Of the 32 households, 22 owned foothill farms with an average size of 0.36 ha. Of these 22 households, 19 continued to use only their inherited foothill farms and did not expand their areas, while the other three households leased out lands from other owners (Table 3.4). The size of their foothill farms became half or less than what their fathers had owned. Ten of the 32 households did not own foothill farms because of land or labor shortage or the expensive maintenance costs of pesticides, chemical fertilizers, tractor rental, transportation, and hiring labor required for extensive maize cultivation. Thus, in most households, the area of farmlands owned by each household, which directly controls the yield of crops, tended to be small compared with what their fathers owned.

Table 3.4 Number of households who inherited farmlands from the owner's father.[a]

The ratio of inherited farmland area from the owner's father	Type of farmland	
	Home garden	Foothill farm
	(household)	
Inherited all area	6	8
3/4 of the area	3	1
1/2 of the area	16	7
1/4 of the area	5	3
Not inherited	2[b]	10
Others	0	3[c]

According to the additional survey of 32 households in December of 2017.

[a] Owners of each household selected the answer from following six options following as: inherited all area, 3/4 of the area, 1/2 of the area, 1/4 of the area, not inherited, and others.

[b] Made new home gardens by converting forests or grasslands.

[c] Leasing out foothill farms from others.

3.3.2. Significance of banana, maize, and coffee in the livelihood of Chagga people

3.3.2.1. Household consumption of banana and maize harvested from farmlands

Households consumed more than 90% of all harvested bananas until about 20 years ago, according to the informants. The second interview survey of the 32 households showed that banana harvested from home gardens was 61% and 69% consumed in households with (22 households) and without foothill farms (ten households), respectively, and there was no significant difference between the two household groups ($p > 0.05$) (Fig. 3.1). This result meant that households have mainly consumed bananas, and, simultaneously, the ratio of bananas shipped to the local market has increased recently.

Of the 32 households, 22 with foothill farms harvested 12% of maize in the home gardens and 88% in the foothill farms. Conversely, the households without foothill farms harvested 100% of maize in their home gardens. An overall 78% and 75% of maize harvested from farmlands was consumed in households with (22 households) and without (ten households) foothill farms, and there were no significant differences between the two household groups ($p > 0.05$) (Fig. 3.1). This indicates that the main purpose of maize cultivation was household consumption, and households without foothill farms began to use home gardens as the main location for maize cultivation for obtaining food.

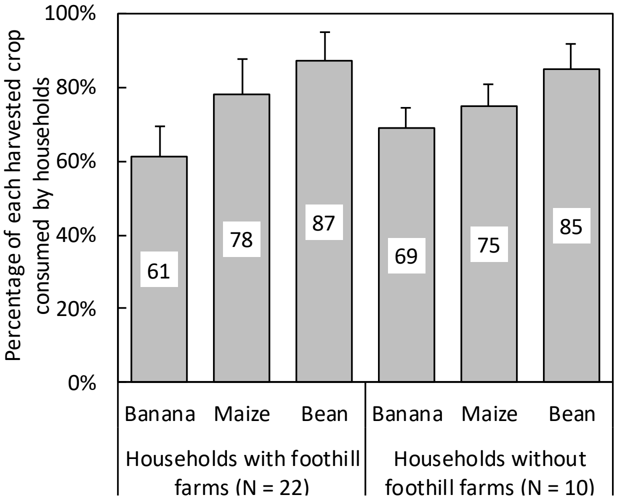

Fig. 3.1. Household consumption rates of harvested banana, maize, and beans from home gardens and foothill farms in two household groups: households with foothill farms (N = 22) and those without foothill farms (N = 10), according to the second interview survey of 32 households in December 2017. Each bar indicates the standard error of the mean in each household group. There were no significant differences in household consumption rates between the two household groups (Student's *t*-test; $p > 0.05$).

3.3.2.2. Income from banana, coffee, and maize harvested in the farmlands

Banana, coffee, and/or maize cultivated in home gardens were sold to the market, as were maize and beans in foothill farms. The total annual income generated by the crops in home gardens and foothill farms was 673,262 Tanzanian shillings (TSh) (ca. 306 US dollars in December 2017) and 707,718 TSh (ca. 321 US dollars) in households with (21 households) and without coffee cultivation (11 households), respectively, of all the 32 households in the second interview survey, and there were no significant differences between the two household groups (*p* > 0.05).

The average income from coffee sales, which is generated by selling all harvested coffee to the local coffee union, accounted for 39% of the total income from agricultural products in households with coffee cultivation (Fig. 3.2). Conversely, more than 90% of household income was generated from coffee sales in the past, according to several key informants. The average income from banana sales was larger than that for other crops in household groups with and without coffee cultivation, and there was a significant difference among them (*p* < 0.05) (Fig. 3.2). In households with coffee cultivation, there was no significant difference in income between banana and coffee sales (*p* > 0.05). According to the merchants at the local market, the amount of bananas delivered by each household has increased in the last ten years. The percentage of household income generated by maize sales was smaller than that by banana or coffee sales in both household groups with and without coffee cultivation, and there were no significant differences between the two household groups (*p* > 0.05) (Fig. 3.2). These results meant that, recently, several smallholder farmers had recognized banana as an important source of income instead of coffee.

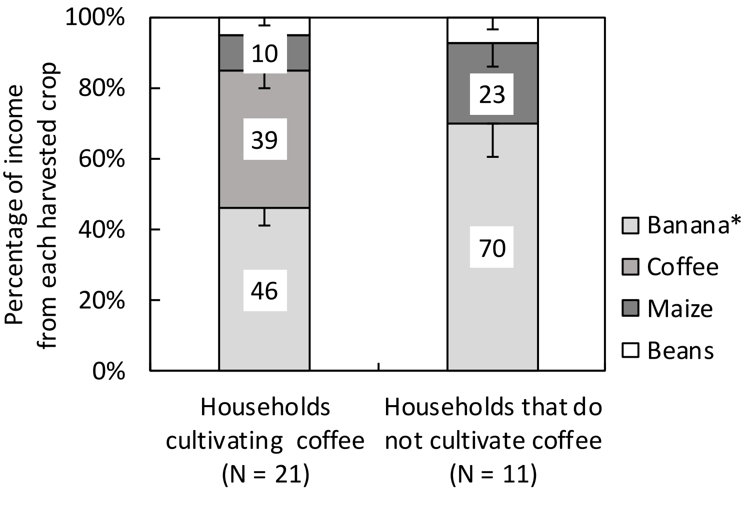

Fig. 3.2. Income ratios of banana, coffee, maize, and beans in total income generated by crop sales in two household groups: households cultivating coffee (N = 21) and households that do not (N = 11), according to the second interview survey of 32 households in December 2017. Each bar indicates the standard error of the mean in each household. *Significant difference between the household groups (Student's *t*-test; *p* < 0.05).

3.3.2.3. Frequency of banana and maize meals in the daily diet

The households' daily staple diet mainly consisted of bananas, maize, and rice. Bananas and maize accounted for 44% and 31% of the daily diet, including breakfast, lunch, and dinner, respectively, which are higher percentages than for rice (Table 3.5). Meanwhile, villagers over 60 years old reported that more than 90% of the daily diet in their childhood was from banana meals and less than 10% from maize meals. Banana meals generally consisted of boiled bananas, vegetables, meat or beans, and were eaten for breakfast, lunch, and dinner, and could be eaten the next day after reheating them. Meanwhile, maize meals were mainly eaten at lunch and dinner in the form of *ugali*. *Ugali* is maize flour mixed with water to create a stiff porridge and usually eaten with green vegetables, beans, fish, and meat at lunch and dinner. Conversely, maize was mainly served as *makande* in the past, which is a traditional boiled-maize meal with corn, beans, and vegetables. It took a whole day to cook *makande*. Rice, which was purchased at retail stores in the village or at the local market, was also eaten with green vegetables, beans, fish, and meat, and was mostly served on special occasions such as Christmas and Easter.

3.3.3. Diverse banana varieties grown in home gardens

3.3.3.1. Classification and characteristics of banana varieties

Eleven varieties of banana were found in the village (Table 3.6, see Picture A1). Each banana variety was distinguished by its characteristics in terms of use, taste, texture, and ease of cultivation based on the Chagga people's indigenous knowledge. Almost all of the 145 households cultivated "*Kisasa*," "*Mchare*," and "*Ndishi*," followed by "*Matoke*," "*Kisukari*," and "*Myenyele*," while less than half of the 145 households cultivated "*Kimalindi*," "*Kipungara*," and "*Mkonosi*" in their home gardens (Table 3.7).

"*Kisasa*," "*Mchare*," and "*Myenyele*" are classified into AA genome groups based on their morphology and were mainly used for cooking in the study village (Table 3.6). There were substantial amounts of *Mchare* plants in most home gardens (Table 3.7). *Mchare* was traditionally used in daily meals and was also one of the most popular varieties sold at the local market. *Kisasa*, which was introduced to the village about 20 years ago from low-altitude areas, was an improved variety that grew fast, required little fertilizer, and was insusceptible to pests and also to wind damage because

Table 3.5 Frequency of different crops in daily diet including breakfast, lunch, and dinner.

	Banana	Maize	Rice	Yam	Wheat	Others
	(%)					
Average	44	31	13	4	6	2

According to the second step survey of 32 households using 24-h dietary recall methods in December 2017.

Table 3.6 Characteristics of 11 representative bananas in the study village.

Genotype[a]	Cultivars[b]	Main usage[c]	Taste	Texture	Market price[d]	Ease of cultivation
AA	*Kisasa*	Cooking, Fruit	Normal	Normal	3	Resistant against pests, growing fast with low fertilizer, resistant to wind
	Mchare	Cooking, Fruit	Normal	Normal	2	Easy to get new suckers
	Mnyenyele	Cooking	Normal	Normal	1	Only one new sucker was obtained
AAA	*Kimalindi* (*Jamaica*)	Cooking, Brewing, Fruit	Little bitter	Soft	4	Normal
	Kitarasa	Cooking	Little bitter	Little fibrous, Soft	5	Normal
	Matoke	Cooking, Fruit	Normal	Very soft	3	Only few new suckers were obtained
	Mrarao	Brewing	Bitter	Soft	5	Suitable for cultivation in warmer areas
	Ndishi (*Ndizi Ng'ombe*)	Brewing	Bitter	Soft	5	Easy to get new suckers
AAB	*Kisukari*	Fruit, Brewing	Little sweet	Normal	4	Susceptible to disease
	Kipungara	Fruit, Brewing	Little sweet	Normal	4	Suitable for cultivation in warmer areas
ABB	*Mkonosi*	Cooking, Roasting	Normal	Hard	6	Suitable for cultivation in warmer areas

According to the participant survey.

[a] Morphological classification was conducted by using information from Simmonds (1996), Karamura et al. (2012), and Higuchi and

[b] Name of cultivars are referred to in the local name in the study village.

[c] Underline indicates the priority for usage.

[d] According to the interview survey at the local market. In order of higher purchase price in the market.

Table 3.7 The situation of cultivation and shipment of 11 representative bananas.

Cultivars	Percentage of cultivated households[a]	Planting density in home gardens[b,c]	Shipment for market[b,c]	Preference of taste[b,e]
Kisasa	99%	+++	+++	
Mchare	98%	+++	+++	2
Mnyenyele	79%	+	-	1
Kimalindi (*Jamaica*)	43%	-	-	
Kitarasa	69%	-	-	
Matoke	82%	+	+	3
Mrarao	66%	-	-	
Ndishi (*Ndizi Ng'ombe*)	97%	++	+	
Kisukari	81%	+	-	
Kipungara	43%	-	-	
Mkonosi	27%	-	- -	

[a] According to the first step interview survey of 145 households.

[b] According to the second step interview survey of 32 households.

[c] +++=Very common, ++=Common, +=Rare, -=Very rare, - -=None

[d] According to the interview survey at the local market. In order of higher purchase price in the market.

[e] In order of preference taste.

of its low height. Although *Kisasa* was mainly used for food in the village, it was less popular for cooking than *Mchare* in the study village (Tables 3.6 and 3.7). According to the merchant, *Kisasa* became popular at the local market because of the increase in demand from urban areas. *Kisasa* was consumed as a dessert banana when ripe and also in cooking in urban areas. Although *Myenyele* was the most popular variety because of its taste among the villagers, it was difficult to increase its number because of its lower ability to grow new suckers compared with other varieties (Tables 3.6, 3.7).

"*Kimalindi*," "*Kitarasa*," "*Matoke*," "*Mrarao*," and "*Ndishi,*" classified into AAA genome groups, were mainly used for cooking and brewing (Table 3.6). They are characterized by a soft texture and/or astringent taste. *Mrarao* and *Ndishi* had an astringent taste and soft texture, and they were mainly used for brewing. *Ndishi* was the most traditional variety because of its ability to grow new suckers. Conversely, cultivation of *Mrarao* was preferred in areas warmer than the study village. *Kimalindi*, *Kitarasa*, and *Matoke* were mainly used for cooking. *Matoke*, which was introduced from the Kagera region in northwest Tanzania, has the smoothest texture among the 11 varieties of banana, especially when boiled, and was a popular variety among the villagers (Table 3.7). *Kimalindi* and *Matoke* were also used for both brewing and dessert owing to their sweet taste and soft texture when ripe.

"*Kisukari*" and "*Kipungara,*" classified into AAB genome groups based on their morphology, were small varieties and eaten as banana desserts (Table 3.6). *Kisukari* was susceptible to disease, while *Kipungara* was considered to be suitable for cultivation in areas warmer than the study village. Although *Kisukari* was cultivated by 81% of the 145 households, it was scarce in each home garden (Table 3.7). Additionally, *Kipungara* was used for brewing in the village and was generally eaten as a banana dessert in other regions.

"*Mkonosi,*" classified into ABB genome groups based on their morphology, was cultivated in 27% of 145 households in the study village (Table 3.6) and was also suitable for cultivation in areas warmer than the study village. There were only a few *Mkonosi* plants in each home garden (Table 3.7).

3.3.3.2. Genetic distances of banana varieties

The results of the principal coordinate analysis of 11 banana varieties indicated that the first principal component divided the genome types into two groups: the A genome (AA/AAA) and the AA × BB hybridization (AAB/ABB); the second component also divided the genotypes into two groups: diploid (AA) and triploid (AAA/AAB/ABB) (Fig. 3.3). The genetic distances of the same genome types were close, and the genetic distances of different varieties used for cooking and brewing were widely spread. There was a relatively large genetic distance between *Matoke* and *Mchare* and between *Mkonosi* and *Mchare*, though these varieties were all cooking cultivars. Conversely, the genetic distance between *Kisasa* and *Mchare*, both cooking cultivars, was minimal. Although the genetic distance of *Kipungara* was close to *Kisukari*, its usage was the same as *Ndishi* and *Murarao*. There were two uses, cooking and brewing, in the AAA group with small genetic distances.

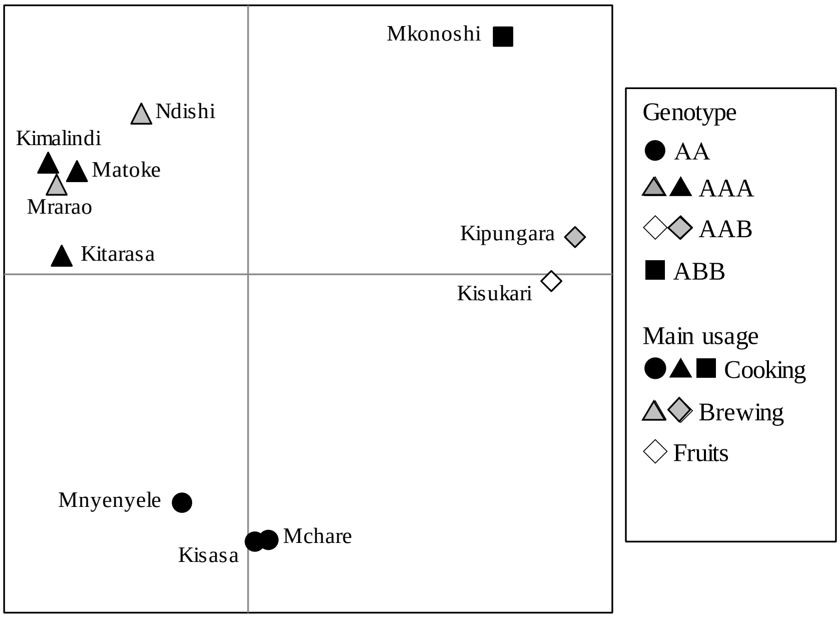

Fig. 3.3. Principal coordinate analysis result of banana genotypes by ISSR. The genetic distances were calculated according to Nei (1972).

3.3.3.3. The diversity of banana used in food and beverages

Ten uses of banana as food and beverage were found in daily life in the study village (Table 3.8, see Picture A2). Specific taste and texture were required for various banana meals, brews, desserts, and roasts. *Macharari* was the most traditional banana meal and was prepared with many banana varieties. When it was prepared using *Myenyele*, it was called *mapoko*, which was served at special events such as wedding celebrations and receptions for important visitors. *Kibulu* was suitable for bananas with slightly hard textures, such as *Mchare* and *Kisasa*, because their pieces had to remain solid after boiling. Conversely, *Matoke*, which had the softest texture, was used for cooking *mtori*, a traditional smooth hot potage. *Makashi* was a form of dry banana as a preserved food and was made from *Ndishi* or *Mrarao*; *Mkonosi* was the best variety for roasting because of its firm texture. The local brew, *mbege*, was made from fermented bananas and finger millet and was traditionally served at all local events. It was also sold at village shops and consumed in daily life. *Ndishi* and *Mrarao*, which has an astringent taste and soft texture, were mainly used for brewing *mbege*. Additionally, surpluses of other varieties were also used for brewing. *Kisukari*, *Kimalindi*, and *Matoke* were the most popular varieties of banana dessert because of their sweet taste.

Table 3.8 Suitable varieties of banana for meal, brew, dessert and roasting in the study village.

Type	Local name	Varieties of banana	Description
Meal	*Kibulu*	*Kisasa, Mchare, Mkonosi*	Like potage. Boiling chopped banana with beans and m*agadi**.
	Kitawa	*Kisasa, Mchare*	Fermented food. Boiling chopped banana with *Magadi*[a], adding fermented milk, and mixing.
	Macharari	*Kimalindi, Kisasa, Kitarasa, Matoke, Mchare, Mnyenyele*	Like stew. Boiling chopped banana with tomato, onion and meat. If banana was used as whole finger of '*Mnyenyele*', it was named *Mapoko*, which was served for a special day.
	Makashi	*Mrarao, Ndishi*	Preserved food. Dry banana. Cook them boiling or milling.
	Memba	*Kisasa, Mchare*	Boiling banana with *Magadi**. Eat with sour milk.
	Mtori	*Kimalindi, Kisasa, Matoke, Mchare, Mnyenyele*	Like potage. Boiling chopped banana with yam, tomato, onion and meat, and mixing until it becomes smooth.
	Ngande	*Kimalindi, Kisasa, Matoke, Mchare, Mnyenyele*	Like potage. Boiling chopped banana with beans, yam, and salt.
Brew	*Mbege*	*Kimalindi, Kisukari, Kipungara, Mchare, Mrarao, Ndishi*	Local brew. Made from fermented banana and finger millet.
Dessert		*Kimalindi, Kisasa, Kisukari, Kipungara, Matoke*	
Roasting		*Mkonosi*	

[a] *Magadi* is a mineral deposit.

3.4. Discussion

3.4.1. The adaptation of cropping practice by the Chagga people to socio-economic changes

The transition from traditional banana-coffee cultivation to banana-coffee coupled with maize cultivation in the home gardens was found to be one of the adaptation strategies of farmland management of the Chagga people to overcome the fragmentation of farmlands, declining ownership of foothill farms, fluctuation of crop values at the market, and changing dietary habits. The efficient management of farmlands was crucial for livelihood in this area where smallholder farmers were dominant (Table 3.1). Therefore, the size of owned farmlands, which directly controls the production in small-scale farming, is one of the most influential factors affecting their decision-making about farmland management, as reported in a previous study (Belay et al., 2017). The Chagga people presumably catered to the increasing number of households by converting forests or grazing lands into home gardens in the past. However, Soini (2005a) indicated that, by 2000, there was little available land remaining for cultivation in areas near the study village. Although all 145 households owned their home gardens, their sizes reduced in recent years, except for a small number of households with male offspring (Tables 3.1 and 3.4). A decrease in the size of foothill farms of each household and a decline in the ownership of foothill farms, as observed in this study, also indicate that land fragmentation has accelerated in low-altitude areas (Tables 3.1 and 3.4). Consequently, smallholder farmers need to adapt appropriate farmland management strategies, including reconsideration of cultivating crop species, to use their limited farmland more effectively and consistently.

The changes in the value of each crop affect the selection of crop species by Chagga people for cultivation in the home gardens. The Chagga people consumed most bananas harvested from home gardens because it forms their important staple food (Fig. 3.1, Table 3.5). It should be noted that bananas occupied 44% of the daily diet in the study village (Table 3.5), which was substantially higher than in other regions in Tanzania, such as Morogoro (10%) (Yamane et al., 2018) and Dar es Salaam (4%) (Mazengo et al., 1997). Simultaneously, around 30–40% of bananas cultivated from home gardens were shipped for the local market, highlighting an important role of bananas for household incomes (Figs. 3.1 and 3.2). Overall, about 15–20% of Tanzania's population, including the Chagga people and others, consider banana as a staple food (Maerere et al., 2010). The populations of the main destinations of bananas exported from the study area recently increased; 2.2, 1.8, and 5.6 times from 2002 to 2012 in Tanga, Moshi, and Dar es Salaam, respectively (The United Republic of Tanzania, 2013).

Furthermore, a paved road from the foot of Mt. Kilimanjaro to local markets in higher elevations was constructed in the 1990s (Kilema Kaskazini village office, 2012), which improved the connection of the local market to urban areas. More recently, villagers were able to deliver substantial amounts of bananas to the local market using motorcycles. Therefore, it is considered that the expansion of the local banana market and the improved distribution increased the significance of banana cultivation for the Chagga people for household incomes.

Maize harvested from both home gardens and foothill farms were also mainly consumed by households, and it contributed to a major part of the Chagga people's daily diet following banana (Fig. 3.1, Table 3.5). Since the 1980s, the consumption of maize increased in the study village from just being served as *ugali* in school lunches to the daily diets of people, being influenced by the dietary habits from urban areas. The introduction of milling machines of maize to the study village in the 2000s also increased the amount of *ugali* in the daily diet by reducing cooking time compared to *makande*. These factors led to an increase of maize meals in the daily diet of the Chagga people from less than 10% in the past to 31% in recent times. Consequently, smallholder farmers need to cultivate more maize today when compared to the past; otherwise, they have to buy from a shortage of it. However, it was observed that many households inherited a small size of foothill farms or did not own foothill farms anymore where smallholders had mainly cultivated maize (Tables 3.1 and 3.4). Such households had to find a place to cultivate maize other than foothill farms, and thereby, some smallholder farmers decided to expand maize cultivation by decreasing coffee cultivation in their home gardens.

Coffee sales had provided a steady and the largest source of income for the Chagga people since the nineteenth century (Moore, 1986). However, the contribution of coffee sales as a household income declined because of a decrease in coffee prices in the world market, thus, reducing coffee cultivation in the home gardens (Fig. 3.1, Table 3.2). Coffee cultivation requires more sophisticated labor-intensive activities than banana cultivation, such as weeding, mulching, pruning, spraying, harvesting, pulping, drying. It also has higher investments in terms of purchasing the pesticides necessary to prevent coffee berry disease and leaf rust (Fernandes et al., 1984). Thus, the coffee extension service provided technical advice for cultivation, and the local coffee union supplied pesticides free of charge to smallholders in this area (Kilema Kaskazini village office, 2012). However, these activities stopped after the 1970s; thereby, the smallholder farmers had to maintain their coffee cultivation alone. Continuing coffee cultivation without adequate support increased the load on the labor force and the production cost for smallholder farmers. The decreasing commercial value of coffee beans, coupled with the increasing difficulty involved in its cultivation, resulted in a decline in the motivation for coffee cultivation in smallholder farmers.

Overall, as reported in previous studies (Ondersteijn et al., 2003; Zorom et al., 2013), smallholder farmers in this study village also continuously attempted to adapt their farmland management to the changing local and global socio-economic circumstances in order to maintain their livelihood. The main crops in the home gardens, banana, maize, and coffee, have experienced transitions against the socio-economical changes. The Chagga people have adapted their farmland management strategies by increasing banana and maize cultivation while decreasing coffee cultivation in the home garden based on the significance of each crop in their livelihood.

3.4.2. The role of diverse genotypes of banana cultivation in maintaining the livelihood of the Chagga people

Besides shifting land management, cultivating diverse genotypes of bananas is another adaptation strategy that Chagga people have adopted to maintain their livelihood under changing socio-economic circumstances. Bananas cultivated in the home gardens in the study village were diverse in terms of their genotypes and use (Fig. 3.3, Tables 3.6 and 3.7). The existence of several genome groups of bananas in home gardens could be attributed to the geographical location of Mt. Kilimanjaro. The Kilimanjaro area was a part of an important caravan route in previous centuries (Moore, 1986), and traders introduced bananas during the sixteenth century (Koponen, 1988): bananas of the AA and AAA groups from Madagascar (De Langhe et al., 2009) and Zanzibar (Simmonds and Shepherd, 1952), and bananas of the AAB and ABB groups from West Africa (Blench, 2009). The geographical advantage of Kilimanjaro highlands contributed to the growth of diverse genotypes of banana in home gardens.

Bananas are a traditional staple food in Chagga society and have been used culturally in their long history. The Chagga people distinguish every banana according to its unique characteristics and according to whether it is cooked or brewed (Tables 3.6 and 3.7), which resulted in a rich and diverse banana food culture in the remote mountainous area, such as *Myenyele* for a special occasion and *Ndishi* for the local traditional brew (Table 3.8). It is considered that the Chagga people have cultivated various types of bananas regardless of their taste, the difficulty of cultivation, and commercial value, in order to maintain their diverse banana food culture.

The Chagga people sophisticatedly differentiated bananas even in a small genetic distance (e.g., *Kisasa* and *Mchare*) and in the same genome group (e.g., the AAA group) (Fig. 3.3, Tables 3.6 and 3.7). It was also found that bananas, which were used for cooking and brewing, had a relatively large genetic distribution (Fig. 3.3). It was reported that diverse genotypes of bananas increased their resistance to diseases such as banana Xanthomonas wilt, banana Fusarium wilt, and nematodes, which caused significant damage in several areas in Africa (Kashaija et al., 2004; Karangwa et al., 2016; Shimwela et al., 2016; Nakato et al., 2018). Another study of genetic diversity of bananas in home gardens on Mt. Uluguru in eastern Tanzania (Higuchi and Takata, 2018) indicated that, if bananas had a low priority as a staple food but a high priority as income, smallholder farmers tended to eliminate banana varieties that did not have commercial value, which led to a decline in the diversity of bananas. In contrast, the importance of bananas as a staple food and the specific usage in Chagga society contributed to maintaining a diverse genotype of bananas in home gardens, which resulted in greater food security in this area for an extended period.

3.5. Conclusion

The Chagga people have adapted their farmland management to maintain their livelihood through optimizing crop species in farmlands and preserving diverse genotypes of bananas in their home gardens. They have altered their farmland management to achieve stable food supply and household income by increasing banana and maize cultivation while decreasing coffee cultivation in their home garden in response to socio-economic circumstances, such as the fragmentation of farmlands, declining ownership of foothill farms, fluctuation of crop values in the market, and changing dietary habits. Those decisions were attributed to the significance of each crop in their livelihood. Diverse genotypes of bananas were retained and accurately distinguished by the Chagga people because they were essential for their food culture. Consequently, bananas have contributed to stable food supply as they are one of the key components of their farmland management for long periods.

Chapter 4

Central roles of livestock and land-use in soil fertility of traditional homegardens on Mount Kilimanjaro

4.1. General

In the home garden system in the Kilimanjaro highlands, organic material cycling between livestock and crop production has been considered to have maintained the productivity of this system. Since all livestock dung including feed residues were collected by each farmer from the stall and applied for farmland as the only fertilizer, it is expected that amount of livestock dung can influence on the soil fertility of the home garden in this system. It is reported that number and type of livestock owned by farmers, especially cattle due to its large body, significantly influenced soil fertility and crop productivity of small-scale farms in east Africa (Bekunda and Woomer, 1996; Baijukya and Steenhuijsen, 1998). Thus, the benefit of application of livestock dung on soil fertility is expected to be more pronounced in Kilimanjaro highlands due to its cool temperature and the high carbon retention capacity of Andosols. However, there are few studies which have quantitatively assessed the relationship between the livestock keeping and soil fertility in the home gardens of Kilimanjaro highlands.

Land management is another factor influencing soil fertility (Gajaseni and Gajaseni, 1999; Salim et al., 2017). The agroforestry systems stored higher soil organic carbon (SOC) stocks compared to monocrop systems (Nair, 2017; De Stefano and Jacobson, 2018). It is reported that the conversion of forest to cropland lead to SOC depletion (Don et al., 2011) and NO_3^- and cation leaching (Shibata et al., 2018). In the Kilimanjaro highlands, most of the home gardens traditionally have had banana-coffee cultivation with intensive management for gaining staple food from banana and cash income from coffee and grasslands with extensive management for collecting feed for their livestock since 1930s. Nevertheless, some of the coffee cultivation areas were converted to the maize cultivation areas in 1990s due to downfall in price of coffee in the world market (Soini, 2005a, b; Kilema Kaskazini village office, 2012). The conversion of land management based on the cultivation crops are also expected to influence soil fertility and the nutrient balance of the home gardens in the Kilimanjaro highlands. However, there are no studies which quantitively investigated the effect of land management on soil fertility.

To understand the relationship between land management and soil fertility of home gardens of Mt. Kilimanjaro, it was hypothesized that livestock and land management are expected to increase the soil carbon and nutrient contents in home garden at the household level. Therefore, this chapter aimed to (1) explore the relationship between the livestock density and soil fertility in the home gardens, and (2) evaluate the effects of different land management (banana cultivation, maize cultivation, and grassland) with special reference to the amount of applied livestock dung on their soil fertility in the home gardens in the Kilimanjaro highlands.

4.2. Materials and methods

4.2.1. Description of the study site

In this study, the representative six home gardens (H1, H2, H3, H4, H5 and H6) were selected based on the livestock densities varied from 1.3 to 9.1 TLU ha^{-1}: a) livestock density was larger than twice of the village average (9.1 and 7.5 TLU ha^{-1} in H1 and H2, respectively), b) livestock density was comparable to the village average (5.8 and 3.9 TLU ha^{-1} in H3 and H4, respectively), and c) livestock density was lower than half of the village average (1.3 and 1.3 TLU ha^{-1} in H5 and H6, respectively) (Table 4.1). The six home gardens were located within 1 km^2 to eliminate the effect of climate, topography, and parent material of soils. The six home gardens have been managed over 50 years since the grandfather or father of current owners of each home garden. For these six home gardens, the C and nutrient flow from outside to the home garden through feed collection were also quantified. The preliminary survey confirmed that there was no significant difference in soil texture and oxalate-extractable Al (Al_o) content of surface and subsurface soils among the six home gardens, suggesting the same geological background for all the home gardens.

The home garden H1 was selected from the above-mentioned six home garden because of its highest livestock density to observe the clear differences in soil fertility among land-uses blocks with different application rate of livestock dung. The home garden of H1 comprised three land-use blocks (Table 4.2); the banana garden with yam and beans (BN), the maize field with beans (MZ) and grassland where field for livestock feed (GR). The most of livestock dung obtained in H1was applied for BN (91%), 9% for MZ and 0% for GR. The area of BN (72% of the total agricultural area in H1) was the largest among the three land-use blocks, followed by MZ (19%), and GR (9%). It had been confirmed that there was no difference in soil texture and Al_o content in surface and subsurface soils among the three land-use blocks according to the preliminary survey.

Table 4.1 Description of home garden of the six households.

	Farmland size	Livestock holding		
		Cattle	Goat	Livestock density
	(ha)	(Head)		(TLU^b ha^{-1})
H1	0.53	6	6	9.1
H2^a	0.24	2	4	7.5
H3	0.56	4	8	5.8
H4^a	0.39	1	10	3.9
H5^a	0.52	0	7	1.3
H6	0.32	0	4	1.3

[a] Households continuing coffee cultivation in BNN.

[b] TLU (tropical livestock unit) is a unit for quantifying a range of different livestock types: 1 TLU = 250 kg of cattle live weight (Jahnke, 1982).

Table 4.2 Description of three land-use blocks in the H1 home garden.

Name	Size	Amount of applied livestock dung	Land history	Cultivation		Application of fertilizer	
	(ha)	(Mg ha^{-1} yr^{-1})[b]		Main	Others	Place	Frequency
BN[a]	0.38	17.5	Used as BN more than 60 years	Banana	Taro, beans	Apply on the surface and put into the deep layer by 60-cm depth	Every day
MZ	0.10	6.6	Used as BN more than 50 years and converted to MZ 17 years ago	Maize	beans	Incorporate by 20-cm depth	Just before seeding (Around July)
GR	0.05	None	Used as GR more than 60 years	Grass		None	None

[a] Cultivated coffee trees with banana untill 1990s.

[b] Dry weight base. Measured in July 2016.

4.2.2. Livestock dung sampling and measurement

The weight of livestock dung in the households was measured in January 2016. The raw weight of cattle dung per home garden was measured once a day for five continuous days, while that of goat dung was measured once a day for five continuous days in H1. The weight of goat dung in other home gardens (H2–H6) was estimated by the head of goats of each household based on the value of H1. Cattle and goat dung were dried at 70°C for one week to determine dry-weights. The weight of dung applied to BN and MZ in H1 was determined based on data from owner interviews and direct measurement as described above.

4.2.3. Soil sampling and analyses

Soil sampling was conducted in January 2016. Soil samples were collected from BN in six home gardens (H1–H6), and soil samples were also collected from MZ and GR, respectively, in H1. Every land-use block was divided into four equal areas, and five soil profiles were made at the middle of the respective quarter areas and the middle of four areas. Every soil profile was divided into five layers, i.e., 0–5, 5–20, 20–35, 35–50 and 50–65-cm depth. Soil samples were collected using a 100-cm^3 stainless core with 5-cm height for the layer of 0–5-cm and using a 300-cm^3 stainless core with 15-cm height for the other layers below. Five subsamples from the layer with the same depth of the five different soil profiles within the same field were composited. Additional soil sampling was conducted for the three land-use blocks of H1 from the same five profiles as mentioned above and the same five layers using an auger. These samples were not composited and used separately for the following analysis.

All soil samples were air dried, ground and sieved using a 2 mm sieve. Soil pH was determined in deionized water at a soil-to-solution ratio of 1:5 using a glass electrode. Bulk density was determined for each layer using a stainless core. Total carbon (TC) and total nitrogen (TN) were quantified by dry combustion method with NC analyzer (Vario Max CHN, Elementer, Germany). Available phosphorus (AvP) was determined by Bray 2 method using 0.03 M acidic ammonium fluoride (Nanzyo 1997), and AvP determination colorimetrically using molybdate. Exchangeable cations (Ca^{2+}, Mg^{2+}, Na^+, and K^+) were determined by atomic absorption spectroscopy (AA-700, Shimadzu, Japan) after extracting with 1 M ammonium acetate at pH 7.0. The sum of the exchangeable cations was assumed to be the total exchangeable base (TEB). To determine the cation exchange capacity (CEC), the residual soil was washed with ethanol after ammonium acetate extraction, and the remaining ammonium (NH_4^+) extracted with 10% sodium chloride (NaCl). The NH_4^+ concentration was determined by using the modified indophenols blue method (Rhine et al., 1998). The stocks of TC, TN, AvP, and TEB were calculated based on the concentrations and the bulk density of each soil layer.

4.2.4. Statistical analysis

The Pearson's correlation coefficient test was used to the relationship between the livestock density and the amount of livestock dung of six home gardens, the relationship between the livestock density and each soil chemical property (soil pH, CEC, TC, TN, AvP and TEB), and the relationship between CEC-TC and TEB-soil pH in each soil layer of six home gardens. The liner regression analyses were also performed on the relationship between the livestock density and each soil chemical property (soil pH, CEC, TC, TN, AvP, and TEB). One way analysis of variance (ANOVA) was used to test the statistical differences among the land-use blocks (BN, MZ, and GR) at a $p < 0.05$ significance level for the means concentrations of each soil chemical property (soil pH, CEC, TC, TN, AvP, and TEB) at each soil layer and for the stock of TC, TN, AvP and TEB throughout the soil profile. When ANOVA indicated significant differences, mean comparisons were performed with the Tukey-Kramer multiple comparison test. The relationship between mean values of each soil chemical property (soil pH, CEC, TC, TN, AvP, and TEB) in three land-use blocks throughout the soil profile of H1 was also subjected to Pearson's correlation coefficient test. All correlation coefficients were obtained using SigmaPlot 11.0 software (Systat Software, Inc., San Jose, CA, USA).

4.3. Results

4.3.1. Effect of livestock density on soil fertility in the soil profiles

4.3.1.1. Relationship between livestock density and amount of livestock dung

H1 with the highest livestock density produced the largest amount of livestock dung (72.6 kg ha^{-1} day^{-1}), while H6 with the lowest livestock density had the smallest amount (3.1 kg ha^{-1} day^{-1}) (Table 4.3). The livestock density was positively correlated with the total dry weight of livestock dung in each household ($p < 0.001$, $r = 0.99$), and thus the presence of cattle and goats in each household directly influenced the amount of livestock dung. The increase of livestock density by 1 TLU ha^{-1} resulted in the increase of livestock dung applied in a home garden by 6.3 kg ha^{-1} day^{-1}.

4.3.1.2. Physico-chemical properties of soils

The differences in soil pH, CEC, TC, TN, AvP, TEB and base saturation among six home gardens were observed not only in the surface layers (0–20 cm) but also in the deeper layers (20–65 cm) (Table 4.4). Soil pH in all the soil layers was the highest in H1 (6.3–6.7), followed by H2, H3, H4

Table 4.3 Amount of livestock dung produced in the six home gardens.

	Weight of dung (kg ha^{-1} day^{-1a})		
	Cattle	Goat	Total
H1	68.7	3.9	72.6
H2	45.9	4.1	50.0
H3	24.2	3.5	27.7
H4	11.1	6.3	17.4
H5	0.0	3.3	3.3
H6	0.0	3.1	3.1

[a]Dry weight base

Table 4.4 Soil physico-chemical properties in banana garden in the six home gardens.

Soil depth	pH (H_2O)						Bulk density (Mg m^{-3})					
(cm)	H1	H2	H3	H4	H5	H6	H1	H2	H3	H4	H5	H6
0–5	6.7	6.2	6.3	5.9	5.0	5.3	0.61	0.68	0.69	0.64	0.77	0.73
5–20	6.5	6.4	6.2	5.7	5.2	5.5	0.61	0.68	0.76	0.63	0.79	0.68
20–35	6.4	6.4	6.2	5.6	5.2	5.4	0.69	0.72	0.76	0.65	0.76	0.73
35–50	6.4	6.4	6.2	5.8	5.4	5.3	0.71	0.71	0.77	0.68	0.81	0.75
50–65	6.3	6.4	6.2	5.9	5.4	5.4	0.73	0.73	0.78	0.73	0.82	0.77
Soil depth	CEC[a] (cmol$_c$ kg^{-1})						Total C (g kg^{-1})					
(cm)	H1	H2	H3	H4	H5	H6	H1	H2	H3	H4	H5	H6
0–5	41.7	42.1	35.6	37.5	32.2	27.0	74.4	73.8	67.6	80.8	71.5	51.2
5–20	44.8	38.8	34.2	33.6	27.1	23.6	75.9	65.6	62.3	64.2	52.3	45.3
20–35	37.8	36.5	32.4	32.3	25.1	23.2	64.2	58.5	52.2	62.7	47.5	40.8
35–50	33.8	37.3	28.3	32.0	23.2	23.2	58.6	58.6	43.2	52.0	40.3	40.6
50–65	32.2	41.3	25.7	31.8	21.4	23.0	53.0	54.8	34.6	39.1	35.5	39.0
Soil depth	Total N (g kg^{-1})						AvP[b] (g kg^{-1})					
(cm)	H1	H2	H3	H4	H5	H6	H1	H2	H3	H4	H5	H6
0–5	6.8	6.8	6.1	6.6	6.3	4.5	0.32	0.17	0.16	0.05	0.10	0.09
5–20	6.7	6.0	5.6	5.4	4.6	3.9	0.37	0.14	0.14	0.03	0.07	0.05
20–35	5.6	5.4	4.9	5.1	4.3	3.6	0.22	0.11	0.10	0.03	0.07	0.05
35–50	5.2	5.5	3.9	4.1	3.7	3.5	0.16	0.08	0.11	0.03	0.05	0.04
50–65	4.8	5.1	3.0	2.8	3.4	3.3	0.11	0.07	0.11	0.03	0.05	0.04
Soil depth	TEB[c] (cmol$_c$ kg^{-1})						Base saturation (%)					
(cm)	H1	H2	H3	H4	H5	H6	H1	H2	H3	H4	H5	H6
0–5	39.6	29.2	30.6	18.9	6.3	7.3	95.0	69.2	85.9	50.4	19.5	27.0
5–20	41.2	25.6	25.8	7.0	4.5	4.8	92.1	66.0	75.3	20.9	16.4	20.2
20–35	33.4	18.9	21.0	5.5	3.0	3.6	88.4	51.8	64.8	17.1	12.1	15.3
35–50	29.4	18.1	17.2	7.8	3.0	2.6	86.9	48.6	60.9	24.5	13.1	11.3
50–65	23.4	21.3	14.8	6.8	2.3	2.6	72.8	51.7	57.5	21.4	10.8	11.5

[a] CEC capacity of exchangeable cation; [b] AvP available phosphorus (Bray II); [c] TEB total exchange base (Na^+ K^+ Ca^{2+} Mg^{2+}).

and the lowest in H5 and H6 (5.0–5.5). Bulk density was the lowest in H1, while that was the highest in H5 in all the soil layers. The CEC, TC, TN, AvP, and TEB were the highest in H1 and H2, followed by H3 and H4, and the lowest in H5 and H6 in almost all the soil layers. The base saturation in H1 was almost full-saturated (72.8–95.0%), while that in H4, H5, and H6 was low (10.8–50.4%). The CEC was positively correlated with TC in the 5–20, 20–35, 35–50 and 50–65-cm layers ($p < 0.05$), and TEB was positively correlated with soil pH in all the soil layers ($p < 0.05$).

4.3.1.3. Relationship between livestock density and soil chemical properties

Soil pH and TEB were positively correlated with livestock density in all the soil layers (Table 4.5). The CEC were positively correlated with livestock density in the top three layers ($p < 0.05$; 0–5, 5–20 and 20–35 cm) and was slightly correlated below 35-cm depth ($p = 0.077$; 35–50 cm). The TC was positively correlated with livestock density in 5–20 and 35–50-cm depth ($p < 0.05$) and was

Table 4.5 Simple regression analysis between livestock density and soil chemical properties in banana garden in the six home gardens.

	Soil depth (cm)	Regression line		
		Slope	Intercept	r^2
pH (H_2O)	0–5	0.13	5.21	0.84**
	5–20	0.11	5.3	0.85**
	20–35	0.11	5.3	0.80*
	35–50	0.1	5.4	0.80*
	50–65	0.09	5.43	0.73*
CEC[a] (cmol$_c$ kg^{-1})	0–5	1.12	20.94	0.70*
	5–20	1.72	24.39	0.93**
	20–35	1.25	24.46	0.82*
	35–50	1.02	24.13	0.58
	50–65	1.07	23.45	0.39
TC (g kg^{-1})	0–5	1.02	64.39	0.19
	5–20	2.3	48.54	0.85*
	20–35	1.63	45.54	0.58
	35–50	1.65	39.97	0.67*
	50–65	1.58	34.15	0.58
TN (g kg^{-1})	0–5	0.13	5.52	0.37
	5–20	0.22	4.2	0.89*
	20–35	0.15	4.01	0.71*
	35–50	0.16	3.44	0.70*
	50–65	0.16	2.86	0.51
AvP[b] (g kg^{-1})	0–5	0.02	0.038	0.83*
	5–20	0.026	-0.008	0.86**
	20–35	0.014	0.02	0.84*
	35–50	0.01	0.026	0.75*
	50–65	0.006	0.034	0.55
TEB[c] (cmol$_c$ kg^{-1})	0–5	2.97	5.94	0.90*
	5–20	3.38	-0.12	0.93**
	20–35	2.74	-0.57	0.93**
	35–50	2.39	0.11	0.97***
	50–65	2.04	0.85	0.89**

*$p < 0.05$, **$p < 0.01$, ***$p < 0.001$, [a] CEC capacity of exchangeable cation; [b] AvP available phosphorus (Bray II); [c] TEB total exchange base (Na^+ K^+ Ca^{2+} Mg^{2+})

slightly correlated in 20–35-cm depth ($p = 0.078$) and 50–65-cm depth ($p = 0.077$), but not in the top layers ($p = 0.39$). Almost 60% of the total soil carbon stock was accumulated in the deeper layers (20–65 cm) in every household studied. The TN was positively correlated with livestock density in the subsoil layers ($p < 0.05$; 5–20, 20–35 and 35–50 cm), while not correlated in the top layer ($p = 0.20$). The AvP was positively correlated with livestock density in the top four layers ($p < 0.05$; 0–5, 5–20, 20–35 and 35–50 cm).

4.3.2. Effects of land management on soil fertility in the soil profiles

4.3.2.1. Physico-chemical properties of soils

Soil pH in BN was close to neutral (6.4–6.8) and was the highest in all the soil layers, followed by that in MZ (5.9–6.1) and GR (5.6–6.0) (Table 4.6). Bulk density was the lowest in BN up to 35-cm

Table 4.6 Soil physico-chemical properties across the five layers from the three land-use blocks in H1 home garden.

Soil depth	pH (H_2O)			Bulk density (Mg m^{-3})		
(cm)	BN	MZ	GR	BN	MZ	GR
0–5	6.8 (0.1) a	6.1 (0.1) b	5.9 (0.1) b	0.61	0.74	0.63
5–20	6.7 (0.1) a	6.2 (0.1) b	5.6 (0.0) c	0.61	0.71	0.66
20–35	6.6 (0.1) a	6.1 (0.1) b	5.6 (0.0) c	0.69	0.72	0.71
35–50	6.5 (0.2) a	5.9 (0.0) b	5.7 (0.0) b	0.71	0.72	0.70
50–65	6.4 (0.0) a	5.9 (0.0) b	6.0 (0.1) b	0.73	0.73	0.72

Soil depth	CEC[a] ($cmol_c$ kg^{-1})			Total C (g kg^{-1})		
(cm)	BN	MZ	GR	BN	MZ	GR
0–5	45.5 (2.8) a	29.8 (0.4) b	29.6 (0.9) b	71.4 (8.2)	53.2 (2.1)	60.7 (2.4)
5–20	40.3 (2.8)	29.0 (0.5)	34.0 (6.3)	64.4 (7.4)	53.1 (1.5)	50.7 (1.3)
20–35	36.0 (1.6) a	24.3 (3.5) b	23.3 (0.6) b	53.6 (2.7) a	49.9 (1.7) a	41.2 (0.9) b
35–50	30.7 (1.1) a	23.4 (2.5) b	24.5 (0.4) b	47.8 (1.3) a	46.3 (1.3) a	35.7 (1.4) b
50–65	28.9 (0.9) a	23.7 (2.7) ab	20.9 (1.8) b	53.3 (5.5) a	46.0 (1.1) a	28.0 (5.0) b

Soil depth	Total N (g kg^{-1})			AvP[b] (g kg^{-1})		
(cm)	BN	MZ	GR	BN	MZ	GR
0–5	6.3 (0.7) a	5.1 (0.1) b	5.9 (0.2) ab	0.39 (0.07) a	0.15 (0.01) b	0.08 (0.01) b
5–20	5.5 (0.7)	4.9 (0.5)	4.9 (0.1)	0.37 (0.06) a	0.15 (0.01) b	0.05 (0.00) b
20–35	5.0 (0.2) a	4.7 (0.2) ab	4.2 (0.1) b	0.23 (0.02) a	0.12 (0.00) b	0.04 (0.00) c
35–50	4.4 (0.2) a	4.4 (0.2) a	3.6 (0.2) b	0.16 (0.03) a	0.08 (0.00) b	0.05 (0.00) b
50–65	5.1 (0.5) a	4.3 (0.1) ab	2.7 (0.5) b	0.10 (0.01) a	0.08 (0.00) b	0.05 (0.00) c

Soil depth	TEB[c] ($cmol_c$ kg^{-1})			Base saturation (%)		
(cm)	BN	MZ	GR	BN	MZ	GR
0–5	39.2 (5.7) a	11.7 (0.9) b	6.3 (1.3) b	86.3 (15.7) a	39.1 (7.0) b	21.2 (8.6) b
5–20	34.3 (4.5) a	11.4 (0.7) b	1.7 (0.2) b	85.1 (39.6) a	39.3 (6.2) b	5.0 (1.4) b
20–35	23.0 (2.9) a	8.8 (0.6) b	0.9 (0.1) c	63.9 (11.1) a	36.4 (23.3) a	3.8 (1.2) b
35–50	14.3 (2.6) a	5.0 (0.3) b	0.8 (0.1) b	46.4 (14.1) a	21.4 (7.4) b	3.3 (1.1) c
50–65	9.8 (0.6) a	4.2 (0.3) b	1.9 (0.4) c	34.0 (3.9) a	17.6 (4.5) b	9.1 (5.0) c

The numbers in parenthesis represent standard errors (N = 5). The different letters indicate that mean values of each layer are significantly different among land-uses ($p < 0.05$). [a] CEC capacity of exchangeable cation; [b] AvP available phosphorus (Bray II); [c] TEB total exchange base (Na^+ K^+ Ca^{2+} Mg^{2+})

Table 4.7 Correlation coefficient among soil properties across the five soil layers in the three land-use blocks in H1 home garden.

	CEC[a] ($cmol_c\ kg^{-1}$)	TC ($g\ kg^{-1}$)	TN ($g\ kg^{-1}$)	AvP[b] ($g\ kg^{-1}$)	TEB[c] ($cmol_c\ kg^{-1}$)
pH (H_2O)					
BN	0.68**	0.46*	0.48*	0.67**	0.77**
MZ	0.26	0.18	0.18	0.75	0.84
GR	–0.14	–0.15	–0.16	0.35	0.54**
CEC ($cmol_c\ kg^{-1}$)					
BN		0.58**	0.57**	0.81**	0.84**
MZ		0.55**	0.58**	0.51**	0.45*
GR		0.52**	0.55**	0.26	0.28
TC ($g\ kg^{-1}$)					
BN			0.99**	0.66**	0.78**
MZ			0.98**	0.62**	0.56**
GR			0.99**	0.65**	0.64**
TN ($g\ kg^{-1}$)					
BN				0.66**	0.77**
MZ				0.65**	0.59**
GR				0.64**	0.64**
AvP ($g\ kg^{-1}$)					
BN					0.86**
MZ					0.96**
GR					0.85**

*$p < 0.05$, **$p < 0.01$, [a] CEC capacity of exchangeable cation; [b] AvP available phosphorus (Bray II); [c] TEB total exchange base (Na^+ K^+ Ca^{2+} Mg^{2+})

depth (0.61–0.69 Mg m^{-3}), while it was the highest in MZ (0.72–0.74 Mg m^{-3}). There was no significant difference in TC between BN and MZ throughout the soil profile, while TC in BN and MZ were significantly higher than that in GR below 20-cm depth. In general, CEC and TN were the highest in BN and the lowest in GR. The AvP and TEB in BN were significantly higher than that in MZ and GR throughout the soil profile. The base saturation of BN was almost full-saturated especially in the shallower layers (0–5 and 5–20 cm), while it was low in MZ and GR, especially below 20-cm depth in GR.

The TC was positively correlated with soil pH, CEC, TN, AvP and TEB in BN ($p < 0.01$) (Table 4.7). The TEB was positively correlated with soil pH ($p < 0.01$) in BN. On the other hand, TC was not correlated with soil pH in MZ and GR ($p > 0.05$).

4.3.2.2 Stock of carbon and nutrients in soil profiles

Total soil carbon stock in all the five soil layers in BN was 245 Mg ha^{-1}, which was 1.06 and 1.36 times larger than that in MZ (231 Mg ha^{-1}) and GR (181 Mg ha^{-1}), respectively (Fig. 4.1). The difference in soil carbon stock between BN and MZ was relatively large in the top layer (1.09 times in 0–5 cm), while that between BN and GR increased with soil depth (1.13 times in 0–5 cm and 1.93 times in 50–65 cm). Total AvP and total TEB in the five soil layers in BN were significantly higher than that of MZ and GR. Total AvP stock in the five soil layers in BN (975 kg ha^{-1}) was 1.9 and 4.2

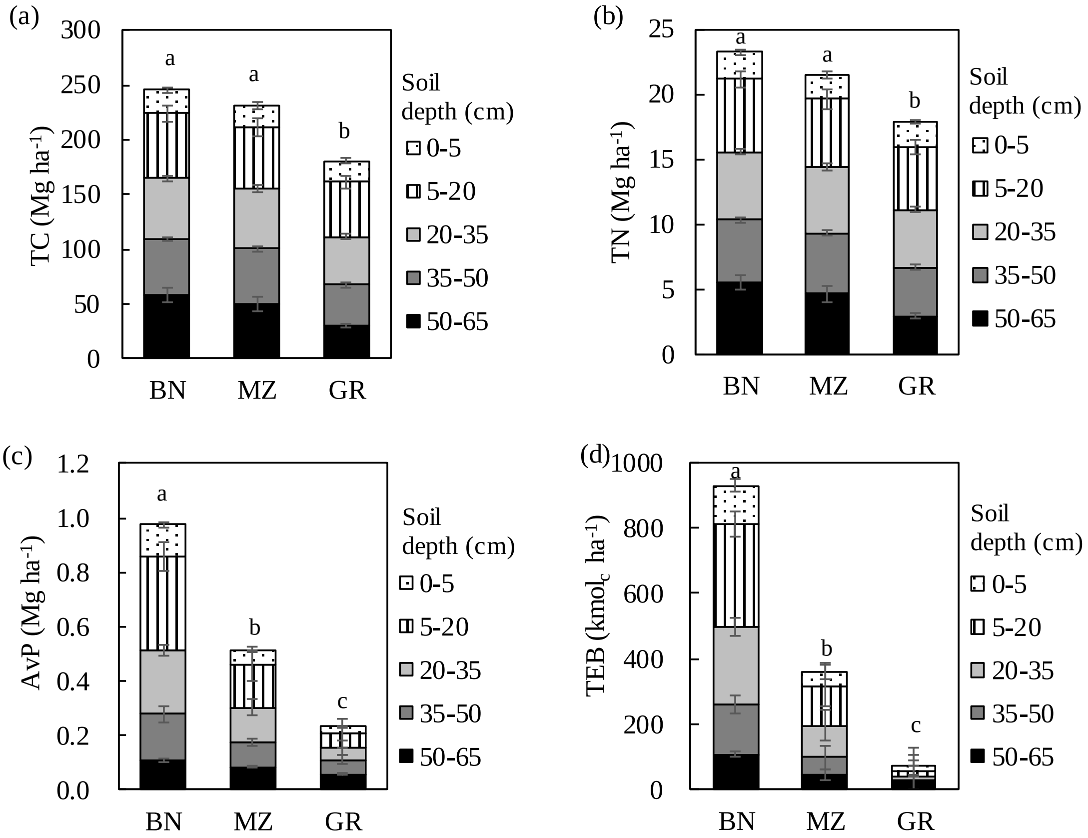

Fig. 4.1 Soil carbon stock and nutrient levels at different soil depths of three land-use blocks in H1 home garden. Each bar indicates the standard error (N = 5). The different letters indicate that mean values of total soil carbon and nutrient stocks in the whole soil profile are significantly different among land-use blocks (p < 0.05). TC total carbon, TN total nitrogen, AvP available phosphorus (Bray II), TEB total exchange base (Na^+, K^+, Ca^{2+}, and Mg^{2+}).

times larger than that in MZ and GR, respectively. Total TEB stock in five soil layers in BN (931 $kmol_c$ ha^{-1}) was 2.6 and 12 times larger than that in MZ and GR, respectively. This tendency was constantly visible in all the soil layers.

4.4. Discussion

4.4.1. Effect of livestock density on soil carbon and nutrients in BN

The positive correlation between TC and livestock density in BN implies that the amount of livestock dung obtained in each household increases carbon stock in soil profiles except at the top layer (Tables 4.3 and 4.5). Farmers in the study village have traditionally applied livestock dung to the surface layer (daily basis) and the deeper layers at 50–60-cm depth for transplanting new banana stalks (several times in a year) for banana cultivation over 60 years. The carbon applied as livestock dung in the deep layer become more stable than that in the surface layer due to the higher stability of organic matter by forming organo-mineral associations and organo-Al/Fe complexes in Andosols (Takahashi and Dahlgren, 2016). On the other hand, the higher decomposition rate of organic matter in the surface layer-resulted in no correlation in the top layer (0–5 cm). While many previous reports have argued that SOC accumulation in organic farming systems is observed mainly in the near-surface layers above 20-cm depth (Bell et al., 2012), the results in this study interestingly showed that SOC in the deeper layers was increased by the livestock dung application in banana cultivation as well as in the surface layers. These results highlighted the potential capacity of the land management in banana cultivation to enhance the carbon sequestration into soils in this region.

Application of livestock dung played an important role in increasing soil nutrients as a source of carbon and nutrients (Table 4.5). The positive correlation between CEC and livestock density and between CEC and TC throughout the soil profile in BN were probably because of carboxylic and phenolic functional groups production in humic substances as previous studies reported (Gao and Chang, 1996). The low correlation between TN and livestock density in the top layer (0–5 cm) is attributable to the various pathways of nitrogen loss such as leaching as NO_3^-, volatilization as NH_4^+, and plant uptake as reported by many previous studies (Fageria and Baligar, 2005; Zheng et al., 2018). The positive correlation between AvP and livestock density suggested that application of livestock dung is an option to increase AvP even in Andosol which has high P-fixation capacity. The increase of AvP in soil profile was possibly caused by supplying inorganic and organic P from livestock dung (Sharpley and Moyer, 2000) and by supplying organic matter that forms metal complexes with Al and Fe thereby increase P solubility and mobility (Haynes and Mokolobate, 2001). The exchangeable cation can be easily lost from soil profile unlike AvP and TC in Andosols due to the abundant rainfall in this area, thereby resulted in the positive correlation of livestock density with TEB and soil pH, respectively.

In this study, it is indicated that the livestock density can be a sensitive indicator of soil chemical properties, particularly soil pH, AvP, and TEB, throughout the soil profile in BN. I estimated the average soil fertility status in BN of the study village based on the simple regression analysis of livestock density (Table 4.5) and the averaged livestock density of the study village (4.4 TLU ha^{-1}) (see Table 2.3); 58.6 g kg^{-1} of TC, 32.0 cmol$_c$ kg^{-1} of CEC, 5.2 g kg^{-1} of TN, 0.11 g kg^{-1} of AvP and 14.8 cmol$_c$ kg^{-1} of TEB. These values are 1.3–3.9 times higher than that of the mean values of soil fertility in the surface soil (5–10-cm depth) from 42 croplands in Tanzania (Funakawa and Kilasara, 2017). However, if the livestock density decreases to 3.4 TLU ha^{-1} or lower, corresponding to 42% of 144 households in the study village, AvP and TEB in the home gardens would become lower than the mean values of soil fertility of 42 croplands in Tanzania. Thus, the increase of livestock density is crucial to maintain high soil carbon and nutrient and high productivity of BN in the home gardens in the Kilimanjaro highlands.

4.4.2. Effects of land managements on soil carbon and nutrients

The difference in soil carbon stock throughout the soil profile in BN, MZ, and GR resulted from the difference of livestock application for each land-use block over past 60 years (Fig. 4.1). The higher accumulation of soil carbon stock in BN was attributed to a large amount of livestock dung application on the surface layer as well as in the deeper layers. Many studies have reported that soil organic carbon content increased with the increase in amounts of organic matter incorporated into soil (Hao et al., 2003; Liu et al., 2018). Furthermore, the structure of BN like agroforestry system could contribute to accumulating more carbon than that in MZ with annual cropping system. Nair (2017) reported an increase in soil carbon stock under agroforestry system past 20 years due to permanent vegetation cover and high root turnover.

Intensive tillage generally accelerates decomposition of soil organic matter in the surface layer (Lal and Kimble, 1997; Palm et al., 2014). The lower TC particularly in the top layer (0–5cm depth) in MZ than that in BN although the difference was not significant was likely caused by the higher soil disturbance due to the cultivation in MZ. On the other hand, the TC below 20-cm depth in MZ has been retained as the same level as that in BN since the land-use blocks was converted from BN to MZ 17 years ago. This result highlighted the high carbon fixing capacity of active Al and Fe in Andosols (Watanabe, 2017). The TC in the top layer in GR was higher than that in MZ because of the high root density in GR. However, lack of fertilizer application to GR and continuous exploitation of grass from GR caused 64 Mg ha^{-1} lower TC stock throughout the soil profile in GR than that in BN. The results in this study suggested that the continuous cultivation and the less input of organic fertilizer resulted in the reduced SOC stock throughout the soil profile while Andosols have the high capacity to sequester carbon in soils compared to other soil types.

After 17 years of altered land-use blocks from BN to MZ, AvP and TEB stock in MZ were decreased by 47% and 61%, respectively, throughout the soil profile (Fig. 4.1). The significant decrease in AvP and TEB in comparison with soil carbon stock was possibly caused by both plant uptake and less replenishment of nutrients in MZ. These results indicated that, if farmers shift the intensive land management in BN to the land management in MZ, soil nutrient status would easily deteriorate in a few decades. In GR, continuous transfer of organic matter to BN and the lack of nutrient replenishment to GR resulted in the lowest nutrient status as well as SOC, although its CEC throughout the soil profile was comparable to MZ. Moges and Holden (2008) also reported that the continuous transfer of organic materials from grasslands into cultivated gardens by farmers resulted in decreasing nutrient contents in grassland while increasing in the cultivated garden in Ethiopia.

The land management as BN is beneficial for maintaining soil carbon and nutrient for long-term agricultural production, while the conversion of land management from BN to MZ and the land management as GR might stimulate soil carbon and nutrient loss. In the Kilimanjaro highlands, banana has been a staple food for the Chagga people for more than five centuries (Fernandes et al., 1984). Meanwhile, banana is also an important cash crop in this area especially after the decline of coffee bean prices in the world market (Soini, 2005b). Therefore, maintaining soil fertility in BN is a vital challenge for the Chagga people to produce food and income through transferring substantial amount of carbon and nutrient from other areas such as MZ and GR using livestock fodder and dung. However, all the areas in home gardens—not only BN but also MZ and GR—should be managed sustainably to produce enough food and fodder for extended periods. It is, therefore, suggested that comprehensive understanding of the sustainable land management of the home garden based on the carbon and nutrient balance of each land-use blocks is needed to evaluate the sustainability of the home gardens and the natural ecosystem in the Kilimanjaro highlands.

4.5. Conclusion

The effects of livestock and land management on soil fertility were quantitatively evaluated in the home gardens in the Kilimanjaro highlands. The results showed that the increase in livestock density of households significantly increased soil pH, CEC, TC, TN, AvP and TEB throughout the soil profile in the field with banana cultivation. Thus, the livestock density plays a significant role in controlling soil fertility throughout the soil profile and could be useful to predict the change of soil fertility along the change in livestock density. The results also showed that a large amount of livestock dung and its application to both the surface and deeper layers for banana cultivation contributed to the best soil fertility throughout the soil profile among the land-use blocks in the home gardens. Better soil fertility in the field with banana cultivation is achieved by the intensive transfer of organic resources from another area via livestock. It is concluded that the relationship between livestock and banana cultivation is a crucial aspect of land management to maintain soil fertility in the home gardens in the Kilimanjaro highlands.

Chapter 5

Carbon and nutrients budget of the Chagga home garden system in the Kilimanjaro highlands

5.1. General

The soil organic carbon (C) content is a critical indicator of soil health. It influences various physical, chemical, and biological soil processes (Lal, 2021). Nitrogen (N), phosphorus (P), potassium (K), and other nutrients are important for crop growth and yield in agricultural production (Fageria and Baligar, 2005). Together with soil stocks, evaluating C and nutrient flows and budgets in agroecosystems can provide valuable indicators for sustainable soil fertility management in smallholder farming systems (Hartemink, 2005; Haileslassie et al., 2006; Mesfin et al., 2020). The inflow and outflow of C and nutrients in a particular smallholder farming system are influenced by the biophysical environment (e.g., soil type, climate, and topography) and farmland management based on the decision-making of each smallholder (e.g., farm size, type of crops, and assets), and influences the sustainability of the entire farming system (Tittonell et al., 2007, 2013; Mesfin et al., 2020). Previous studies in SSA showed that the nutrient balance of smallholder farming systems with limited organic resources is strongly influenced by land management, such as cultivating crop species, distance from homestead, frequency of tillage (Baijukya et al., 2005; Zingore et al., 2007; Moges and Holden, 2008; Goenster et al., 2014), number of cattle holdings (Baijukya and Steenhuijsen, 1998; Throne and Tanner, 2002), and socioeconomic conditions of households (Haileslassie et al., 2006; Tittonell et al., 2009; Mesfin et al., 2020).

As described in Chapter 4, differences in livestock holdings and land management affected soil fertility of the Chagga home garden system. Livestock density was positively correlated with soil pH, available P (AvP), and total exchangeable bases (TEB: Ca^{2+}, Mg^{2+}, K^{+}, and Na^{+}) throughout the soil layers (0–65 cm), while C and N concentrations in the top layer (0–5 cm) were not correlated with livestock density, probably because of C loss through soil respiration and N loss through crop growth and leaching at the surface soil. The differences in crop types cultivated and resource allocation within the home garden also influenced the C and nutrient stocks of the home garden. The intensive application of livestock dung to the soil surface (0–20 cm) and deep layers (20–65 cm) resulted in the largest stock of AvP and TEB throughout the soil profile in the banana garden. Evaluating C and nutrient budgets and flows linked with C and nutrient stocks of home garden systems can explain the influence of soil fertility management by the Chagga people on agricultural production of the home garden system. In this study, to clarify the factors for maintaining the home garden system, I 1) quantified the soil C and nutrient flow in three land-use blocks (banana garden, maize field, and grassland) and the internal flows between farmland and livestock in the home garden, and 2) quantified the external nutrient flow across the inside and outside of the home garden.

5.2. Materials and methods

5.2.1. Description of the study site

To quantify C and nutrient flows under different farmland management practices in the home garden system, a representative home garden (H1) was elected from the households surveyed in a previous study (refer to Table 4.2). To apply the H1 home garden results to the village level, the nutrient balance of six representative home gardens (H1, H2, H3, H4, H5, and H6) was selected in a previous study (see Table 4.1). The C and nutrient flows from outside into the home garden through feed collection were also quantified for these six home gardens.

5.2.2. Framework analyzing for C and nutrients flows at the home garden

Figure 5.1 presents a simplified model of C and nutrient (N, P, K, Ca, and Mg) flows in the home garden system in the study village. The home garden consisted of two compartments: farmland and livestock. The direction of C and nutrient flow is indicated by arrow diagrams: the internal flow of the home garden and the external flow. Internal flow included transport from farmland to livestock and livestock to farmland. External flow includes external inflow and external outflow. For H1, both internal and external flows of the home garden were quantified for the three land-use blocks, as shown in Fig. 5.1. For the external inflow, the amount of C biomass in primary production was later distributed to crop harvest, feed collected from within the home garden, and root litter in the soil. Biological N-fixation by legumes was quantified as amount of N in the external inflow. Simultaneously, the amounts of C and nutrients in the feed from outside the home garden, which are communal grassland and forests, foothill farms, and other villages, were quantified as a component of the external inflow. For the external outflow, the amounts of C and nutrients in the harvested crops, those in the soil solution leached from the soil, and CO_2 released from the soil surface through soil organic matter decomposition (i.e., soil respiration) were quantified. For internal flows of the home garden, the amounts of C and nutrients in the livestock dung, which were applied to the farmland and feed for livestock collected from the farmland were quantified. For farmland, the budget of C and nutrients in the soil in the three land-use blocks was calculated as follows:

C budget in soil = Inflow (livestock dung + primary production)
– Outflow (feed + crop + soil solution + soil respiration)

Nutrient budget in soil = Inflow (livestock dung + biological N-fixation)
– Outflow (feed + crop + soil solution)

There were no apparent signs of soil erosion. Nitrogen gaseous loss was not considered in this study due to the previous study reporting that N_2O emission in the managed home garden in Kilimanjaro was low (Gütlein et al., 2017). For livestock, the balance of C and nutrients for livestock production was calculated as follows,

C and nutrient balance in livestock =
Inflow (feed from inside and outside the home garden)
– Outflow (livestock dung)

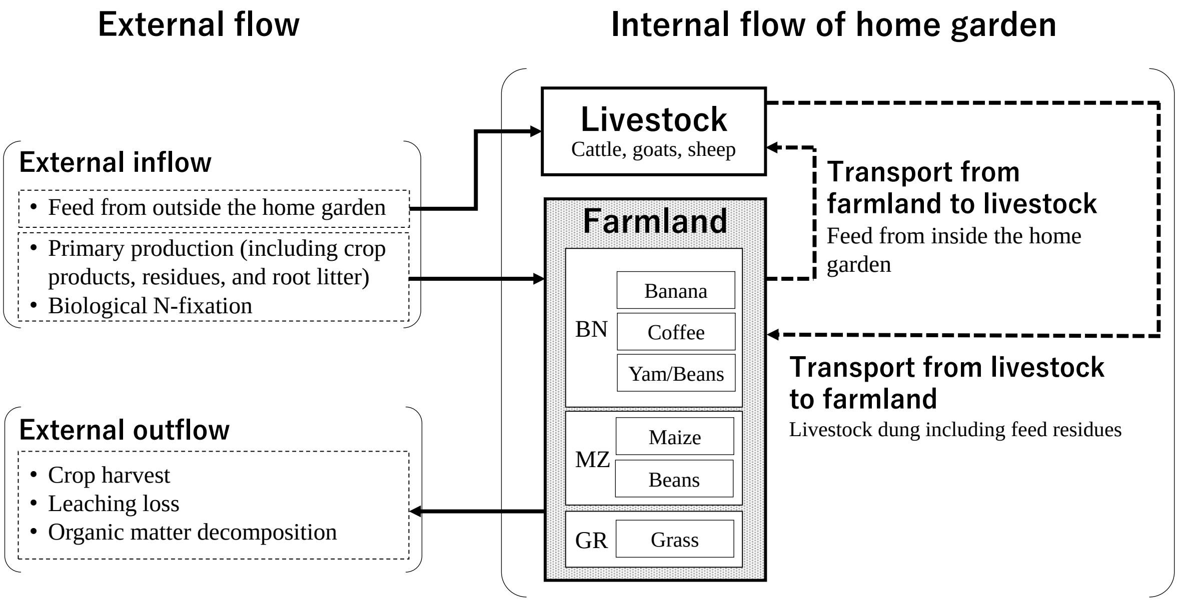

Fig. 5.1 Schematic diagram of the home garden system and C and nutrient flows. The farmland consisted of three land-use blocks: banana garden (BN), maize field (MZ), and grassland (GR).

Based on the H1 results, the nutrient (N, P, K, Ca, and Mg) budget in the farmland soil at each of the remaining five home gardens (H2 to H6) was calculated using the livestock dung as the primary nutrient inflow to the farmland soil and the feed and crops harvested as the primary nutrient outflow from the farmland soils.

Nutrient budget in the farmland soil = Inflow (livestock dung)
– Outflow (feed and crops)

This section did not include the C budget because of the lack of soil respiration data, a major outflow of C from farmland, from the five home gardens. The amount of feed collected from outside the home garden was calculated based on the interview survey for the same six home garden owners, and then C and nutrient amounts were quantified.

5.2.3. Analyses of livestock dung and plant materials

The annual weight of livestock dung, which was applied to three land-use blocks in H1 (BN, MZ, and GR) and five home gardens (H2, H3, H4, H5, and H6), was obtained from a previous study (refer to Chapter 4). The raw weights of feed and feed residues, including banana leaves, banana stalks, grass, tree leaves, and residues of maize and beans in six home gardens, were measured once a day for five successive days in January 2016 and December 2017, respectively.

The yields of the main crops (banana, coffee, maize, beans, and yam) from the six home gardens were recorded as follows. The six home garden owners recorded the number of harvested banana bunches. Rainy season yields were recorded in April, May, and November 2017. Dry season yields (June–October and December–March) were recorded in June and December 2017, and the average was used to estimate the yield during the dry season. The sum of the rainy and dry seasons was used as the annual banana yield. The yearly yields of coffee, maize, beans, and yams from April

2017 to March 2018 were obtained through an interview survey of the owners of the six home gardens.

The inflow of C by root litter in H1 was examined for representative crops of each land-use block: banana for BN, maize for MZ, and grass for GR. The annual root litter of bananas was estimated using the banana root-shoot ratio (Turner and Lahav, 1983), and the aboveground biomass was used as feed during the year. The root biomass of maize was estimated based on the measured aboveground biomass in 10 × 10 m^2 in three replications in the MZ and the root-to-shoot ratio (Turan et al., 2010). The biomass of grassroots was calculated based on the root biomass of 1 × 1 m^2 in three replicates in GR, and the annual rate of grassroots litter was assumed to be 67% of the root biomass in the tropical grassland (Wang et al., 2019). Nitrogen contribution by beans (*Phaseolus vulgaris*) through biological N-fixation was estimated to be 50% of the total plant uptake in the aboveground biomass (Baijukya and Steenhuijsen, 1998).

Livestock dung was oven-dried at 70 °C for one week. Plant samples, including crops (banana, coffee, maize, beans, and yam), feed (banana leaves, banana stalks, maize, and beans residues, grass, tree leaves), and root litter (banana, maize, and grass roots), were rinsed in distilled water to remove soil materials, oven-dried at 70 °C for 48 h, and weighed and milled. The TC and TN contents were determined by the dry combustion method using an NC analyzer (Vario Max CHN, Elementer, Germany). The concentration of total phosphorus (TP) was determined colorimetrically (UV-VIS spectrophotometer UV-1200, Shimadzu, Japan), and the concentrations of K, Ca, and Mg were determined by atomic absorption spectroscopy (AA-700, Shimadzu, Japan) after wet digestion with nitric-sulfuric acid.

5.2.4. Environmental monitoring

The experimental plots (10 m × 10 m) were set at the center of each land-use block (BN, MZ, and GR) in H1. Environmental monitoring was conducted from April 2017 to October 2018. Prior to the start of environmental monitoring, monitoring equipment was installed inside each experimental plot in December 2016 to eliminate the effects of soil disturbance associated with the setting of the experimental plots. Soil temperature at 5 cm depth was measured with a thermistor probe (108 Temperature Probe, Campbell Scientific, Inc.) in two replicates. The volumetric water content of the soil at 0–20, 30, and 60 cm depths was measured with a time domain reflectometer (CS616 Water Reflectometer, Campbell Scientific, Inc.) in two replicates. Data were recorded at 30 min intervals using data loggers (CR-1000, Campbell Scientific, Inc.).

5.2.5. Soil solution composition and nutrient fluxes

The soil solution sampling equipment was set inside the experimental plots at three land-use blocks in H1 from April 2017 to October 2018. Soil solutions were collected using porous cups (Daiki Rika Kogyo, Soil Water Extractor, 1.1 cm inner diameter, and 6 cm height). The porous cups were inserted into the soil to a depth of 60 cm, where banana roots mainly extend, with five replications for each land-use. These porous cups were connected to 50 ml syringes on the ground and kept under depressed conditions by hand immediately before collecting soil solutions. Soil solution collection was carried out six times in 2017 and five times in 2018 during the rainy season, immediately after large rain events. Sample solutions were filtered through a 0.45 µm filter and stored at 4 °C in the dark prior to analysis. The pH of the solution was determined using a glass electrode. The concentrations of dissolved organic C (DOC), inorganic C (IC), and total dissolved N (TDN) in the solution were determined using a total organic C analyzer (TOC-VCSH, Shimadzu, Japan). The concentrations of NH_4^+-N and NO_3-N in the solution were determined using a continuous flow injection analyzer (AS-50; Aqualab Co., Ltd., Tokyo, Japan). The concentrations of dissolved organic N (DON) were calculated by subtracting the inorganic N (NH_4^+-N and NO_3-N) concentrations from the TDN concentrations. The total phosphorus (TP) concentration was determined colorimetrically using a UV-VIS spectrophotometer (UV-1200, Shimadzu, Japan). The concentrations of K^+, Ca^{2+}, and Mg^{2+} were determined by atomic absorption spectroscopy (AA-700, Shimadzu, Japan).

The unsaturated hydraulic conductivity characteristic of the Mualem-van Genuchten functions (Mualem and Dagan, 1978; van Genuchten, 1980) is written as follows:

$$K = K_\mathrm{s} \times {S_\mathrm{e}}^{0.5} \times \left[1 - \left(1 - {S_\mathrm{e}}^{\frac{1}{m}}\right)^m\right]^2$$

$$S_\mathrm{e} = \frac{(\theta - \theta_\mathrm{r})}{(\theta_\mathrm{s} - \theta_\mathrm{r})} = [1 + (-\alpha h)^n]^{-m}$$

where S_e is effective saturation, K_s (m day^{-1}) is the saturated hydraulic conductivity, θ_s (L L^{-1}) and θ_r (L L^{-1}) are the saturated and residual water content, n is a fitting parameter, and $m = 1-1/n$. K_s and water retention curves for undisturbed soils were experimentally obtained using 100 cm^3 sampling cylinders at 30 cm and 60 cm depths in three replicates in each land-use block. Based on the water retention curve, pressure heads were calculated from volumetric soil water content monitored every 30 min using a time-domain reflectometer and data loggers. Using the soil moisture retention curves obtained for each soil layer, the soil hydraulic parameters were calculated using a retention curve computer program (van Genuchten et al., 1991). The water flux between 30 cm and 60 cm depths was calculated as

$$q_w = -K(h)\frac{[h_{30} + (-30)] - [h_{60} + (-60)]}{(-30) - (-60)}$$

where q_w is the water flux (m s^{-1}), $K(h)$ is the unsaturated hydraulic conductivity (m s^{-1}), and h is the pressure head (m). The annual fluxes of the soil solutions were calculated as follows:

Annual water fluxes =
((monthly water flux from April to October 2017)
+ (monthly water flux from April to October 2018)) / 2
+ (monthly water flux from November 2017 to March 2018)

In this study, the water flux between 30 cm and 60 cm depth was used as the annual water flux at a depth of 60 cm. Since it was assumed that the effect of C and nutrient flux during the dry season was minimal, the annual flux of each element in the soil solutions was calculated as the product of the measured concentrations and the monthly water fluxes during the rainy season (April and May in 2017 and 2018, and November in 2017).

5.2.6. Measurement of CO_2 efflux from the soil surface

Soil respiration consists of plant root and microbial respiration. This study measured the CO_2 efflux rate using the closed-chamber method (Shinjo et al., 2006) to exclude plant-root respiration. Polyvinyl chloride (PVC) columns (diameter, 11 cm; height, 40 cm) were inserted 20 cm deep into the soil in five replicates inside the experimental plots at three land-use blocks in H1 in April 2017. The linear increase in the CO_2 concentration in the PVC column in both the dry and rainy seasons was measured for 30 min prior to gas sampling. The gas samples in the headspace of the PVC column were collected at 0 min and 30 min into pre-evacuated 30 ml glass vials using a 50 ml syringe between 8:00 and 11:00 h, twice or thrice a month in the rainy season and once a month in the dry season from April 2017 to October 2018. The gas samples were analyzed using an infrared CO_2 analyzer (ZFP9AA11; Fuji Electric, Tokyo, Japan).

To estimate the annual CO_2 flux, we used the following equation:

$$C_{em} = a\,M^{b}$$

where C_{em} is the hourly CO_2 efflux rate (mol C ha^{-1} h^{-1}), M is the volumetric soil moisture content (L L^{-1}), b is a coefficient related to the contribution of the soil moisture, and a is a constant. The influence of the soil temperature was neglected in this simulation because the seasonal fluctuation of the soil temperature was limited to only 6 °C (15–21 °C). The annual CO_2 flux was calculated as follows:

Annual CO_2 fluxes =
((monthly CO_2 flux from April to October 2017).
+ (monthly CO_2 fluxes from April to October 2018)) / 2
+ (monthly CO_2 fluxes from November 2017 to March 2018)

5.2.7. Statistical analysis

Pearson’s correlation coefficient test was used to determine the relationship between livestock density and the amounts of N, P, K, Ca, and Mg in livestock dung applied to farmland soil and feed collected from farmland soil of the six home gardens, and between the livestock density and the inflow of C, N, P, K, Ca, and Mg in feed collected from outside the six home gardens. The normality of the data for the amounts of N, P, K, Ca, and Mg in livestock dung and feed collected from farmland soil of the six home gardens, and the inflow of C, N, P, K, Ca, and Mg in feed collected from outside the six home gardens was tested. Pearson’s correlation coefficient was applied to the soil moisture and air/soil temperature data to assess the environmental factors that control the seasonal fluctuation in the CO_2 efflux rate in the three land-use blocks. In all cases, a p-value < 0.05 was considered significant. All statistical analyses were performed using SigmaPlot 11.0 (Systat Software Inc., San Jose, CA, USA).

5.3. Results

5.3.1. Livestock dung and plant materials

Livestock dung, including feed residues, was applied every day under banana trees in BN, and the C and nutrients applied by livestock dung were the highest in BN among the three land-use blocks in H1 (Table 5.1). In MZ, livestock dung was applied just once before planting maize from June to July, similar to other households, amounting to approximately one-third of that of BN. Dung was not applied in GR.

The types of feed collected at each land-use block were different. The main feeds collected were banana leaves and stalks from BN, maize residues from MZ, and grass and tree leaves from GR (Table 5.2). The amount of N lost from the soil through feed collection was the largest in BN, followed by GR and MZ. The amount of K lost from the soil in BN through feed collection was seven and five times higher than that in MZ and GR, respectively. For crop harvest, bananas, yam, and a small amount of beans were harvested from BN, whereas maize and a small amount of beans were harvested from MZ. Harvested crops are primarily consumed by the family or sold in the local market if there is a surplus. The amounts of N and K lost from the soil through crop harvest in BN were more significant than those in the MZ (Table 5.3). The annual C applied to soil from root litter in GR was the largest, accounting for 2.4 Mg C yr^{-1} ha^{-1}, followed by BN (1.1 Mg C yr^{-1} ha^{-1}) and MZ (0.5 Mg C yr^{-1} ha^{-1}). Biological N-fixation was estimated as 3.8 and 4.5 kg ha^{-1} yr^{-1} in BN and MZ, respectively, based on the amount of beans and beans residues harvested (Tables 5.2 and 5.3).

According to the interview survey of the owner of H1, some of the feed supplied to their livestock was collected from outside the home garden, accounting for 30% of banana leaves, 30% of banana stalks, 90% of grass, 60% of tree leaves, 95% of maize residues, and 86% of bean residues in all feed (Table 5.4). They were collected from his land or forest outside the home garden, his foothill farm located at a low altitude, and purchased from other villages.

Table 5.1 C and nutrients in livestock dung, including feed residues at BN, MZ, and GR in H1.

	Amount of livestock dung[a]			C and nutrients					
	Cattle	Goat	Feed residue	C	N	P	K	Ca	Mg
	(Mg ha^{-1} yr^{-1})			(Mg ha^{-1} yr^{-1})	(kg ha^{-1} yr^{-1})				
BN	22.6	1.3	3.2	12	618	84	475	165	98
MZ	7.5	0.4	2.6	4	202	27	155	68	32
GR	0.0	0.0	0.0	0	0	0	0	0	0

[a] Dry weight base

Table 5.2 C and nutrients in feed collected from BN, MZ, and GR in H1.

	Amount of feed[a]						C and nutrients					
	Banana leaves	Banana stems	Maize residue	Beans residue	Grass	Tree leaves	C	N	P	K	Ca	Mg
	(Mg ha^{-1} yr^{-1})						(Mg ha^{-1} yr^{-1})	(kg ha^{-1} yr^{-1})				
BN	4.4	12.1	0.0	0.1	0.1	0.7	6.6	465	23	536	66	50
MZ	0.2	0.6	2.6	0.1	0.1	0.6	1.7	60	9	73	20	10
GR	0.0	0.0	0.0	0.0	9.1	0.7	4.1	210	16	85	35	21

[a] Dry weight base

Table 5.3 C and nutrients in crop harvest at BN and MZ in H1.

	Amount of crop harvest[a]				C and nutrients					
	Banana	Maize	Beans	Yam	C	N	P	K	Ca	Mg
	(Mg ha^{-1} yr^{-1})				(Mg ha^{-1} yr^{-1})	(kg ha^{-1} yr^{-1})				
BN	4.7	0.0	0.4	0.2	2.1	153	6	122	4	6
MZ	0.2	3.3	0.5	0.0	1.7	61	11	109	6	5

[a] Dry weight base

Table 5.4 C and nutrients in feed collected from outside the home garden H1.

Amount of feed from outside[a]						C and nutrients					
Banana leaves	Banana stems	Maize residue	Beans residue	Grass	Tree leaves	C	N	P	K	Ca	Mg
(Mg yr^{-1})						(Mg yr^{-1})	(kg yr^{-1})				
0.7	2.0	4.9	0.2	8.7	0.7	7.1	328	33	238	73	39

[a] Dry weight base

5.3.2. Environmental monitoring

Rainfall was generally concentrated in the rainy season, i.e., April–May and November, with an annual rainfall of 1571 mm (Fig. 5.2). The soil moisture was consistently higher during the rainy season than during the dry season in the three land-use blocks. The annual soil temperatures at a depth of 5 cm were 18.6 °C, 19.8 °C, and 19.7 °C in BN, MZ, and GR, respectively.

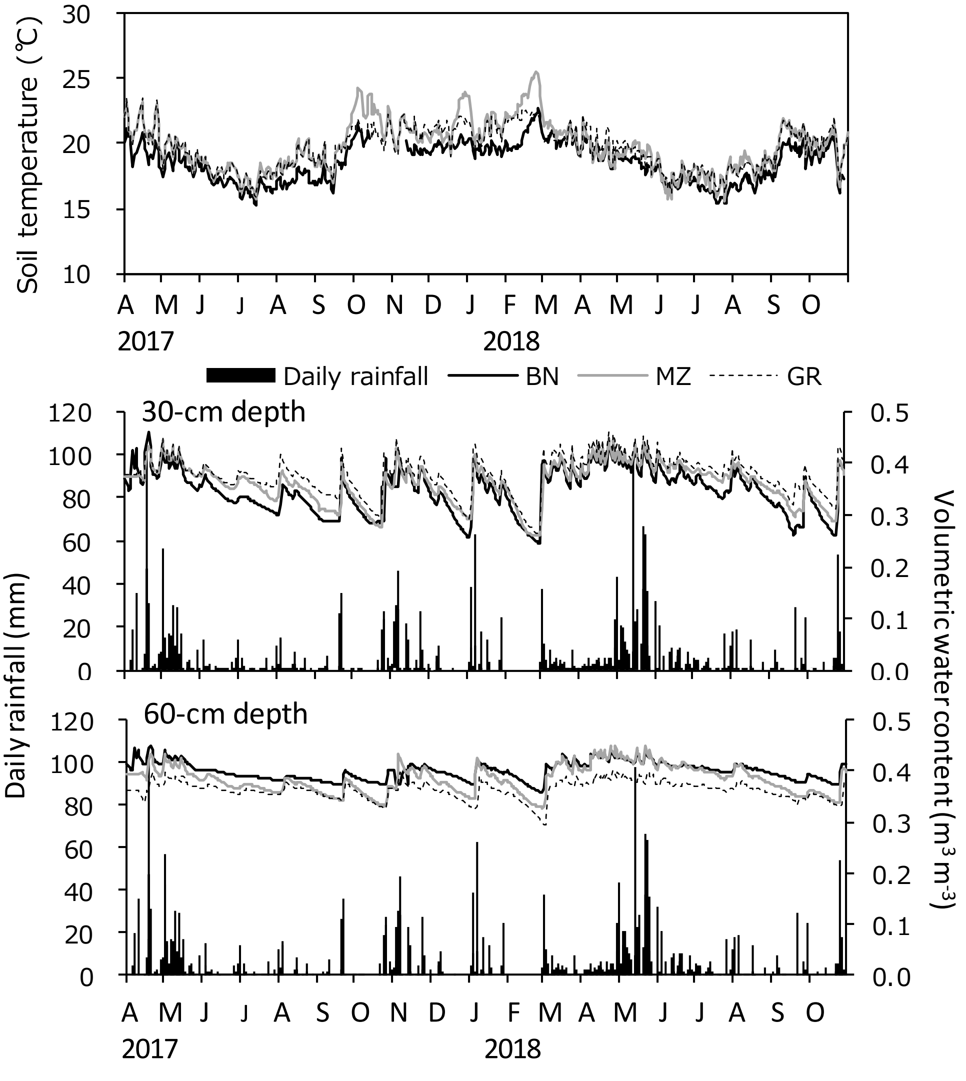

Fig. 5.2 Daily soil temperature at 5 cm depth, rainfall, and volumetric water content at 30 and 60 cm depths during the experiment at BN, MZ, and GR in H1.

5.3.3. Soil solution composition and nutrient fluxes

The pH of the soil solutions at 60 cm depth in BN was slightly higher than that in MZ and GR (Table 5.5). The concentrations of DOC and IC in the soil solution in BN were the highest among the three land-use blocks. The concentrations of NO_3 were relatively higher than those of DON and NH_4 in the BN and MZ. The concentration of K was substantially higher in BN than that in MZ and GR, whereas the concentrations of Ca and Mg were comparable in BN and MZ. TP concentrations in the soil solution in all land-use blocks were not detected. The annual leaching loss of all elements was the largest in BN among the three land-use blocks, especially in DOC, IC, NO_3-N, and K^+.

5.3.4. CO_2 efflux from the soil surface

A higher soil respiration rate was observed during the rainy season than during the dry season in all land-use blocks (Fig. 5.3). The CO_2 efflux rate in all land-use blocks was significantly correlated with soil moisture at 0–20 cm depth ($p < 0.01$, Appendix Fig A1), while it did not correlate with soil temperature in the surface layer ($p > 0.05$). The estimated annual CO_2 flux in MZ was the largest, accounting for 6.1 Mg C yr^{-1} ha^{-1}, followed by BN (5.7 Mg C yr^{-1} ha^{-1}) and GR (2.8 Mg C yr^{-1} ha^{-1}) (Figs. 5.3 and A1).

Table 5.5 Concentrations and fluxes of DOC, IC, DON, NH_4-N, NO_3-N, K^+, Ca^{2+}, and Mg^{2+} in the soil solution at 60 cm depth during the long and short rainy seasons at BN, MZ, and GR in H1.

	Sampling season[b]		pH	Concentration[a]							
	Year	season		DOC	IC	DON	NH_4^+-N	NO_3^--N	K^+	Ca^{2+}	Mg^{2+}
				(mg C L^{-1})		(mg N L^{-1})			(mg L^{-1})		
BN	2017	big rain	7.3±0.1	4.3±0.3	6.6±0.3	1.2±0.7	0.3±0.2	4.8±1.4	29.1±0.7	5.0±0.4	3.3±0.2
		short rain	7.7±0.1	6.9±0.7	4.9±1.2	0.0±0.0	0.5±0.1	4.5±1.8	12.7±5.5	1.2±0.1	1.4±0.3
	2018	big rain	8.1±0.0	8.2±0.5	12.7±0.2	0.5±0.2	0.2±0.1	7.3±0.9	13.4±0.5	5.7±0.2	4.7±0.2
MZ	2017	big rain	6.7±0.1	2.1±0.4	2.4±0.1	0.2±0.0	0.0±0.0	0.4±0.1	0.5±0.2	3.2±0.5	1.5±0.1
		short rain	6.9±0.1	4.6±1.5	2.8±0.0	0.8±0.8	0.7±0.4	1.9±1.6	1.2±0.3	2.0±0.5	3.0±0.5
	2018	big rain	7.7±0.0	2.8±0.4	4.2±0.1	0.3±0.1	0.1±0.0	0.3±0.0	0.8±0.1	4.3±0.2	2.7±0.2
GR	2017	big rain	6.5±0.0	2.4±0.7	0.9±0.0	0.1±0.1	0.0±0.0	0.2±0.0	0.2±0.1	0.9±0.1	0.6±0.2
		short rain	6.8±0.0	2.4±0.5	0.8±0.0	0.0±0.0	0.5±0.0	0.1±0.0	0.4±0.2	0.1±0.0	0.2±0.1
	2018	big rain	7.0±0.0	2.1±0.2	1.0±0.0	0.1±0.0	0.1±0.0	0.1±0.0	0.0±0.0	0.3±0.1	0.0±0.0

	Flux								
	Water	DOC	IC	DON	NH_4^+-N	NO_3^--N	K^+	Ca^{2+}	Mg^{2+}
	(mm yr^{-1})	(kg C ha^{-1} yr^{-1})		(kg N ha^{-1} yr^{-1})			(kg ha^{-1} yr^{-1})		
BN	372	21.8	28.5	2.6	1.0	16.0	58.2	14.6	11.1
MZ	574	8.3	9.0	0.6	0.2	2.8	2.3	9.4	6.6
GR	869	7.6	2.9	0.2	0.5	0.4	0.8	1.4	0.8

[a] The results of pH and concentrations are the means ± standard errors. [b] The sample number at each sampling season: big rain in 2017: n=4, short rain in 2017: n=2, big rain in 2018: n=6

5.3.5. Balance of nutrients in farmland soil in home garden with different livestock holdings

The data for the amounts of N, P, K, Ca, and Mg in livestock dung and feed collected from farmland soil of the six home gardens were normally distributed. Livestock density correlated with the inflow of all nutrients through livestock dung application to the farmland soil of the six home gardens ($p <$ 0.001) and was also correlated with the outflow of all nutrients by feed harvested from the farmland soil of the six home gardens ($p <$ 0.05; Fig. 5.4). The balance of P, Ca, and Mg in farmland soil improved for the home gardens with higher livestock density, while the balances of N and K were negative in all six home gardens (Table 5.6).

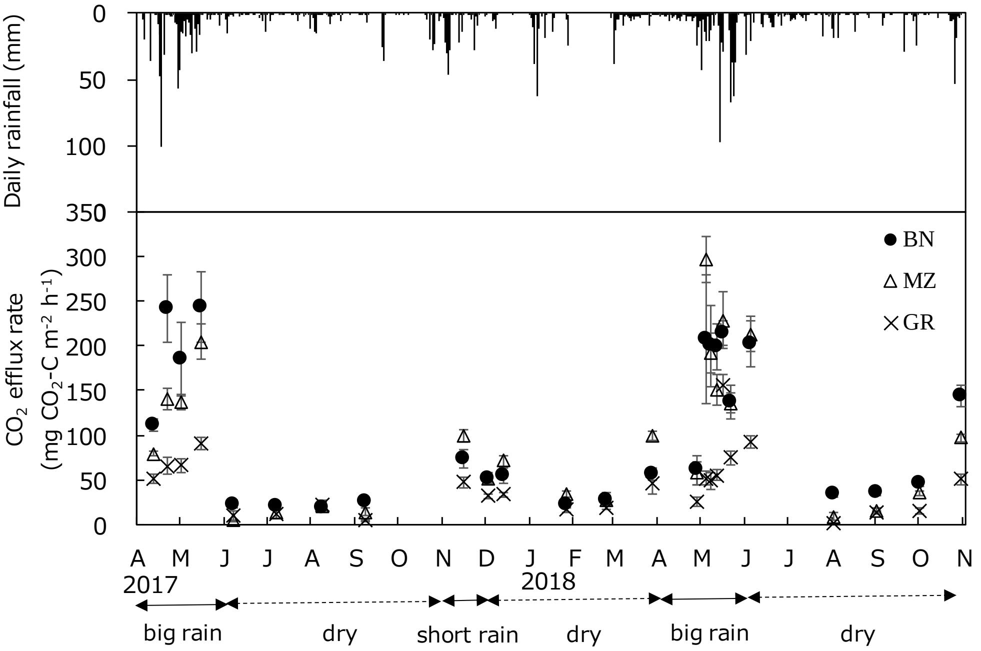

Fig. 5.3 Daily precipitation and CO_2 efflux rates at BN, MZ, and GR in H1.

Table 5.6 Balance of nutrients in farmland soil of the six home gardens.

Home garden	N	P	K	Ca	Mg
	(kg ha^{-1} yr^{-1})				
H1	-5	39	-144	70	31
H2	-79	28	-151	47	20
H3	-124	13	-189	18	4
H4	-166	6	-192	7	-2
H5	-113	-7	-124	-13	-9
H6	-151	-7	-143	-14	-11

Balance of nutrients: Livestock dung – (feed from home garden + crop harvest)

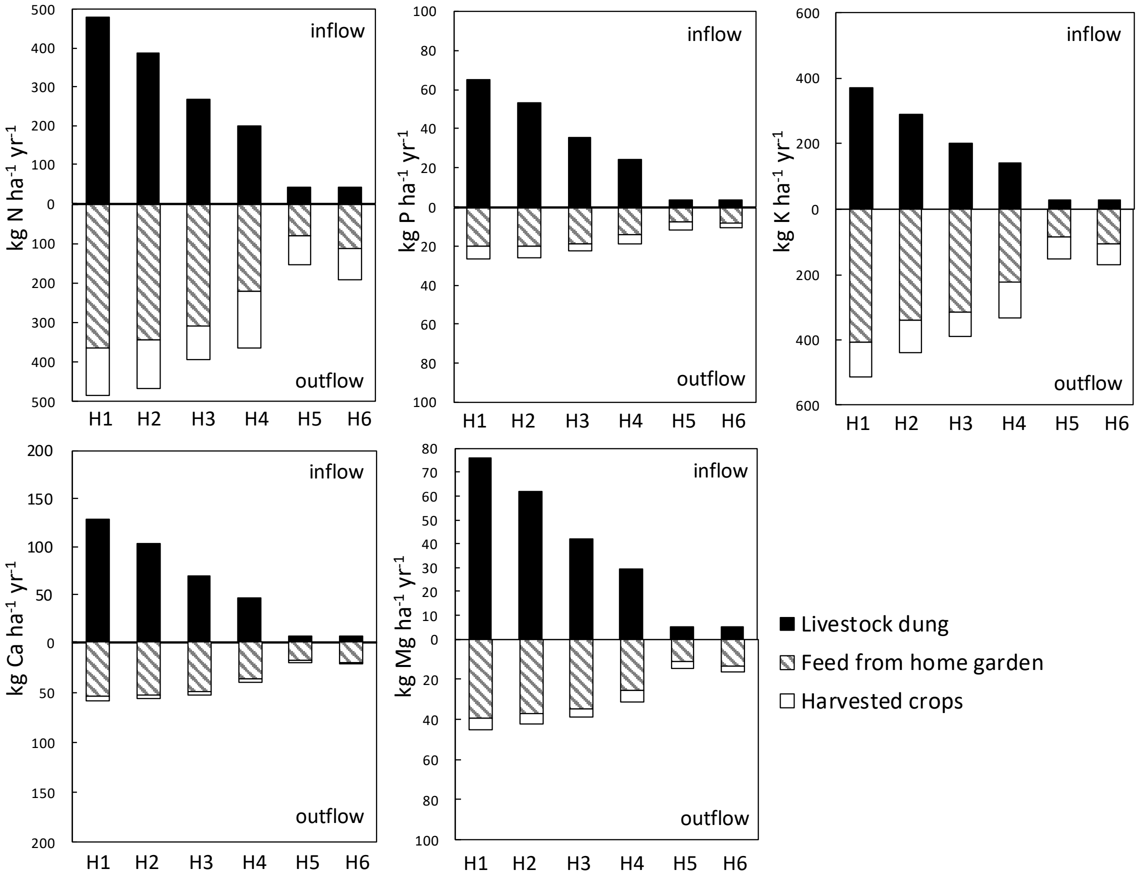

Fig. 5.4 Inflow and outflow of N, P, K, Ca, and Mg in the farmlands of the six home gardens. Inflow: livestock dung including feed residues; outflow: feed and crops harvested from farmland.

5.3.6. Amount of C and nutrients in feed collected from outside the home garden

All six households collected feed, including banana leaves and stalks, maize residues, grass, and tree leaves outside the home garden. Banana leaves and stalks were supplied by households in the village with surpluses or purchased from other villages. Maize residues were collected around September after cultivation in foothill farms owned or rented by each household. Grass and tree leaves were collected from small grasslands and forests in the study village or purchased from other villages. The amount, type, and collection place of feed varied among households due to differences in cultivated crops, size of home gardens, and number and type of livestock. The data for the inflow of C, N, P, K, Ca, and Mg in the feed collected from outside the six home gardens were normally distributed. The annual amounts of C and nutrients in the feed collected from outside the six home gardens were positively correlated with livestock density ($p < 0.05$; Fig. 5.5). The average percentages of feed collected from the outside six home gardens to the total amount of feed supplied to livestock were 45%, 40%, 47%, 33%, 44%, and 40% for C, N, P, K, Ca, and Mg, respectively.

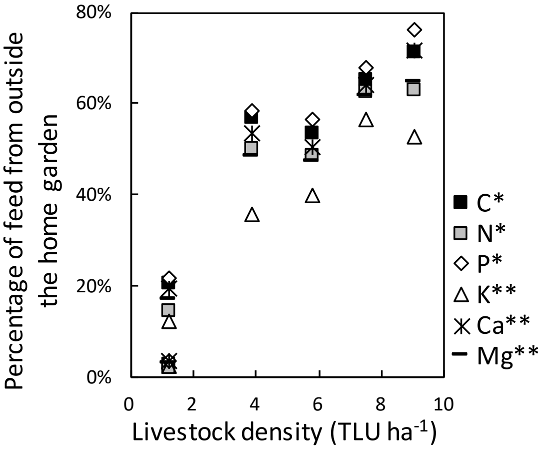

Fig. 5.5 Percentage of C and nutrients in feed collected from outside the home garden to the total amount of feed supplied to the livestock in the six home gardens. Correlation coefficient between livestock density and percentage of C and nutrients in feed collected from outside the home garden: * $p < 0.05$, ** $p < 0.01$.

5.4. Discussion

5.4.1. Effect of farmland management at BN, MZ, and GR on C and nutrients budget in the soil

The C and nutrient budgets exhibited different characteristics in each land-use block. The C budget in the soil in BN was positive, whereas that in MZ and GR was negative (Table 5.7). Banana cultivation is essential for smallholder farmers because bananas are the staple food for the Chagga people. Therefore, the application of livestock dung was prioritized in BN (Table 5.1), resulting in the largest C inflow in BN among the three land-use blocks. A previous study reported that smallholder farmers preferentially allocate available fertilizers to grow the main food security crop (Zingore et al., 2007). Intensive C application to BN likely accelerated C accumulation in the soil profile by stabilizing soil organic matter by forming stable organo-mineral and Al/Fe–humus complexes in Andosols (Takahashi and Dahlgren, 2016). Organic matter decomposition was the largest C outflow in all land-use blocks, whereas DOC and IC were negligible (Table 5.7). The amount of organic matter decomposition in MZ was comparable to that of BN, although the amount of livestock dung applied to MZ was one-third of that in BN (Fig. 5.3, Tables 5.1 and 5.7). This was attributed to continuous plowing in the MZ, which destroyed soil aggregates (Pabst et al., 2016). Higher average soil temperature in MZ (19.8 °C) due to the bare period after harvesting maize may also increase soil respiration in MZ, compared to BN (18.6 °C) (Fig. 5.3).

The budget of N in BN was negative but accounted for only 0.07% of the total N stock in the soil profile (0–65 cm) in BN (Table 5.7; Appendix Table A3). Therefore, inflow of N balanced with outflow of N in BN. Surprisingly, only 3% of the N added to livestock dung was lost from BN through NO_3^--N leaching, despite the continuous application of a substantial amount of livestock dung for more than 60 years (Table 5.7). The low NO_3^--N leaching in BN in our study (Table 5.5) could be explained by the large amount of organic N applied as livestock dung accumulated in the

Table 5.7 C and nutrients in the internal flow of the home garden and the external flow in the home garden system of H1.

		(Mg yr^{-1})	(kg yr^{-1})				
		C	N	P	K	Ca	Mg
Farmland							
BN	Inflow						
(0.38 ha)	Internal inflow	4.5	235	32	180	63	37
	Livestock dung	4.5	235	32	180	63	37
	External inflow	3.7	1	0	0	0	0
	Primary production	3.7					
	Biological N-fixation		1				
	Outflow						
	internal outflow	2.5	177	9	204	25	19
	Feed from inside the home garden	2.5	177	9	204	25	19
	external outflow	3.0	66	2	68	7	7
	Crop harvest	0.8	58	2	46	1	2
	Leaching loss	0.0	7	0	22	6	4
	Organic matter decomposition	2.2					
	Budget in soil	2.8	-6	21	-92	30	11
MZ	Inflow						
(0.1 ha)	Internal inflow	0.4	20	3	15	5	3
	Livestock dung	0.4	20	3	15	5	3
	External inflow	0.4	0	0	0	0	0
	Primary production	0.4					
	Biological N-fixation		0				
	Outflow						
	internal outflow	0.2	6	1	7	2	1
	Feed from inside the home garden	0.2	6	1	7	2	1
	external outflow	0.8	6	1	11	2	1
	Crop harvest	0.2	6	1	11	1	0
	Leaching loss	0.0	0	0	0	1	1
	Organic matter decomposition	0.6					
	Budget in soil	-0.2	8	1	-3	2	1
GR	Inflow						
(0.05 ha)	Internal inflow	0.00	0.0	0.0	0.0	0.0	0.0
	Livestock dung	0.00	0.0	0.0	0.0	0.0	0.0
	External inflow	0.32	0.0	0.0	0.0	0.0	0.0
	Primary production	0.32					
	Biological N-fixation		0.0				
	Outflow						
	internal outflow	0.20	10.5	0.8	4.3	1.7	1.1
	Feed from inside the home garden	0.20	10.5	0.8	4.3	1.7	1.1
	external outflow	0.14	0.1	0.0	0.0	0.1	0.0
	Crop harvest						
	Leaching loss	0.00	0.1	0.0	0.0	0.1	0.0
	Organic matter decomposition	0.14					
	Budget in soil	-0.02	-10.6	-0.8	-4.3	-1.8	-1.1
Whole farmland	**Budget in soil**	**2.6**	**-8**	**20**	**-99**	**31**	**11**
Livestock	Inflow						
	Feed from inside the home garden	2.9	193	11	215	29	21
	Feed from outside the home garden	7.1	328	33	238	73	39
	Outflow						
	Livestock dung	4.9	255	34	196	68	40
	Balance in livestock	**5.1**	**266**	**9**	**257**	**34**	**19**
Whole home garden system	External inflow	11.6	330	33	238	73	39
(0.53 ha)	Primary production	4.4					
	Biological N-fixation		2				
	Feed from outside the home garden	7.1	328	33	238	73	39
	External outflow	3.9	72	4	80	9	8
	Crop harvest	1.0	64	4	57	2	3
	Leaching loss	0.0	8	0	22	7	5
	Organic matter decomposition	2.9					
	Internal flow						
	Transport from livestock to farmland						
	Livestock dung	4.9	255	34	196	68	40
	Transport from farmland to livestock						
	Feed from inside the home garden	2.9	193	11	215	29	21
	Balance (exteranl inflow - external outflow)	**7.7**	**258**	**30**	**158**	**64**	**31**

surface soil. Organic N mineralized slowly; therefore, bananas may absorb NO_3^- effectively over the years throughout the soil profile by the deep roots. Previous studies have reported that significant amounts of organic N in manure were immobilized after application to soil (Maeda et al., 2003; Cavalli et al., 2016), and the longer period of uptake and longer rooting depth of perennial crops may suppress N leaching (van Es et al., 2006). Consequently, the applied livestock dung was effectively consumed to produce crops and feed in BN. The P budget in BN and MZ was positive because of the continuous application of livestock dung and the high P fixation capacity of Andosols.

Despite the high K input through livestock dung in BN, the most negative K budget among the three land-use blocks was observed in BN (Table 5.7). The outflow of K in BN was dominated by K removal through large amounts of banana harvests, while K leaching was small. This was attributed to banana's high K absorption (Emaga et al., 2007) and high soil cation exchange capacity (CEC) in Andosols. Previous studies have also reported a negative K balance in banana-growing areas in SSA (Baijukya and Steenhuijsen, 1998; Braber et al., 2021). For H1, 6% of the exchangeable K^+ stock in the soil profile (0–65 cm) in BN was depleted annually (Appendix Table A3). However, the concentration of exchangeable K in the surface soil in BN (2–4 $\mathrm{cmol_c\ kg^{-1}}$) was higher than other Tanzanian croplands, where the average concentration of exchangeable K was 1.2 $\mathrm{cmol_c\ kg^{-1}}$ (Funakawa et al., 2012). Soini (2005a) reported that banana yield on the southern slopes of the Kilimanjaro highlands has been maintained since the 1980s. Therefore, the negative K budget in BN does not immediately influence the banana yield. This is because exchangeable K is replenished by the non-exchangeable K^+ pool, which is substantially larger than the exchangeable K^+ pool in Andosols (Yanai et al., 1995; Jalali, 2006). Therefore, the negative K budget in BN has been overcome by a combination of intensive livestock dung application and the high K supply and retaining capacity of Andosols.

The budgets for N and K in farmland soil at the village scale were negative (Table 5.6). There are several options for improving the nutrient budget of home garden systems. The use of urine for farmland soil, in addition to livestock dung, is an option. However, urine infiltrates the ground floor and is lost in this system. In western Niger, the millet grain yield in plots with manure and urine was 13% higher than that in plots with manure only (Ikpe and Powell, 2002). Given the negative N budget in the home garden at the village scale (Table 5.6), the introduction of leguminous crops or forage with large biomass and high N fixation to the home gardens could be an option to supply crops, feed, and maintain soil fertility inside the home garden.

5.4.2. Role of external inflow of C and nutrients in maintaining the Chagga home garden system

The Chagga home garden system had been considered to maintains productivity through the internal cycling of C and nutrients inside the home garden (Fernandes et al., 1984). However, our results revealed that maintaining soil fertility in this system relied heavily on the external inflow of C and nutrients, mainly as a feed for livestock (Table 5.7, Fig. 5.5). Approximately 33% to 47% of the supplied feed on a carbon and nutrient basis was collected from outside the home gardens at the village scale. Livestock plays an essential role in the system and provides multiple benefits as an asset, food source, and social and cultural meaning, and improves soil fertility (refer to Chapter 4; Bender, 2013). Therefore, smallholder farmers want to increase the number of livestock. However, this study showed that the higher the livestock density, the greater the dependence on the external inflow of C and nutrients as feed (Fig. 5.5). In the case of H1, the owner collected the feed from his land or forest outside the home garden within the village, his foothill farm located at a low altitude, and other villages. The amount of feed collected from outside the home garden was greater than that collected from inside the home garden (Table 5.7). Previous studies in other areas of SSA have reported that intensive and continuous external inflows of resources into farmlands caused severe depletion of soil fertility in the surrounding ecosystem (Rufino et al., 2011; Tittonell, 2014). The declining soil fertility in the GR due to the lack of livestock dung application and the continuous C and nutrient removal by feed collection can also occur in surrounding ecosystems outside the home garden in the Kilimanjaro highlands. The evaluation of C and nutrient flow on a regional scale, including inside and outside the home garden, is important for assessing the sustainability of the entire home garden system in the Kilimanjaro highlands.

5.5. Conclusion

I found that smallholder farmers' decisions on resource allocation determined the C and nutrient flows of the system, which consequently affected the soil fertility of the system. Livestock dung was preferentially allocated to banana fields because of the importance of bananas in the livelihood of the Chagga people, resulting in a positive C and nutrient budget, except for N and K, in the soil of the banana garden. Although the N and K budgets in BN were negative, banana production was likely maintained by the large amount of organic N in livestock dung, which suppressed N leaching, and the continuous replenishment of K^+ from Andosols. Therefore, the combination of livestock dung application and banana cultivation was a key practice for maintaining the soil fertility of this system by storing C in the soil and suppressing nutrient loss in Andosols in the Kilimanjaro highlands. Notably, this system largely relied on external inflow from outside the home garden to fulfill the demand for feeding; hence, it is essential for the home garden system to maintain this inflow.

Chapter 6
General discussion and conclusion

This study revealed the adaptation of farmland management strategies by smallholder farmers against socioeconomic changes and the effect of soil fertility management on C and nutrient flows of the Chagga home garden system in the Kilimanjaro highlands. This section discusses the advantage of the agricultural practice combined with livestock dung application and banana cultivation and the future perspective of the Chagga home garden system based on the results in the previous chapters and presents a conclusion.

6.1 Fragmentation of home gardens

The reduction in farmland area was a major challenge faced by smallholder farmers in the study village (refer to Chapter 3). They reduced coffee cultivation within their home gardens, maintained and expanded banana cultivation, and started maize cultivation to maintain the productivity and profitability of their limited home garden area. In the Chagga tradition, sons inherited home gardens from their fathers by dividing the land. In the past, when home gardens could not be inherited or when home gardens were too small, forests and grasslands were converted to farmland to ensure productivity. However, it was reported that there was no land available for farmland in the 2000s (Soini 2005a,b). Soini (2005b) reported that 47% of the households inherited less than 0.4 ha and 21% only 0.1 ha in the Kirua Vunjo Division, neighboring the study village. The average size of the 32 surveyed home gardens was 0.31 ha. However, if subdivisions of home gardens were to increase and only about 0.1 ha were to be inherited, it would be difficult to maintain a livelihood. The population growth rate in the Kilema Kaskazini ward from 2002 to 2012, including the study village, was 1.1 times (The United Republic of Tanzania, 2012). This population growth rate is moderate compared to that of large cities, such as Moshi City (population growth rate was 1.8 times) and Dar es Salaam (population growth rate was 5.6 times) (The United Republic of Tanzania, 2012). This is most likely because of the decision of the villagers to leave the village and find employment in the cities when they were not able to secure enough home garden areas to maintain their livelihoods. This study also found that several people in the age group of 20–40 years resided in urban areas to work in the study village (Appendix Fig. A2). The subdivision of home gardens is, therefore, not expected to accelerate in the future.

6.2 Cultivation of banana, coffee, and maize in the home gardens

Stable banana production in home gardens has maintained the livelihoods and social culture of the Chagga people. Banana cultivation requires fertile soil and rainfall of 1,000 mm or more (Cattan et al., 2006), which limits production areas. The Kilimanjaro highlands are favorable for production because of fertile volcanic soil and abundant rainfall. The Kagera and the Kilimanjaro regions accounted for 59% and 17% of the total banana production in Tanzania, respectively (The United

Republic of Tanzania, 2016). It has been reported that Tanzania will continue to experience rapid population growth through 2100 (UN, 2019), and urban demand for bananas is expected to continue rising, especially among the Chagga people who have moved to the cities. Therefore, the significance of bananas as a staple food and cash crop for the Chagga people is expected to continue. In contrast, the importance of coffee for livelihood, which had been the foundation of the home garden system since the 1930s, has declined. Factors such as introducing improved species and rising global market prices can encourage the continuation of coffee cultivation. However, the profitability of coffee and bananas can be considered to be equal today (refer to Chapter 3). Many farmers may have decided to decrease coffee cultivation, which requires significant investment and labor compared to banana cultivation. Maize cultivation is more efficient in low-altitude areas, where temperatures are warmer and where there are no slopes and tractors can be used. Maize cultivation in home gardens requires an extra three months compared to the time required for cultivation in foothill farms. Although there has been an increase in the importance of maize as a staple food in livelihoods, it is unlikely that all banana cultivation will shift to that of maize. This is because of the high suitability of soil and climate in the Kilimanjaro highlands for banana cultivation, the importance of bananas as a staple food, and their social and cultural significance in Chagga's livelihood. Maize is grown throughout Tanzania and has a large domestic market. From a land-use perspective (refer to Chapter 5), purchasing maize is more efficient than cultivating maize in home gardens. Consequently, it is predicted that home gardens will continue to be primarily used for banana cultivation, with maize cultivation continuing in a smaller area as needed. On the other hand, the decision to continue with coffee cultivation will be left to each household.

6.3 Soil fertility management of the home garden system

Farmland management by combining the application of livestock dung with banana cultivation was an efficient practice to accelerate carbon accumulation and suppress nutrient losses in the Kilimanjaro highlands having dominant Andosols and high rainfall (refer to Chapters 4 and 5). Livestock manure was the sole fertilizer in this system, with livestock density defining soil fertility. The traditional knowledge that owning more livestock contributes to higher agricultural productivity was also correct in terms of the C and nutrient balance by this system. Smallholder farmers wanted to own livestock, especially cattle, for manure, assets, and cultural meaning. Of the 145 surveyed households, 103 households kept cattle, according to an interview survey conducted in 2016. The number of cattle, however, differed among households. Cattle keeping requires large stall sheds, large amounts of feed, healthcare, and funds to purchase new cattle. Factors such as the household's economic situation, labor availability, and land area were considered to affect the possibility of holding cattle.

The application of livestock dung in home gardens has been a key practice in maintaining soil fertility for long periods. In particular, the results of high N input and low N leaching (< 3%) (refer to Chapter 5) were an important strategy in soil fertility management, especially in SSA agriculture, where N deficiency is a concern (Stoorvogel et al., 1993; Nziguheba et al., 2021). Several studies in SSA reported that the leaching loss of the N applied as mineral fertilizer to maize fields was 9%–13% in Tanzania (clay, 150 kg N ha^{-1}) (Zheng et al., 2019), 47% in Zimbabwe (sandy, 120 kg N ha^{-1}) (Nyamangara et al., 2003), and 40% in Kenya (sandy clay loams, 200 kg N ha^{-1}) (Russo et al., 2017). In terms of C accumulation, it is difficult to accumulate the input C source owing to the high organic matter decomposition rate in tropical agriculture (Sugihara et al., 2012; Purwanto and Alam, 2019). However, in the Kilimanjaro highlands, applied livestock dung tends to accumulate in the soil because of the properties of Andosols, which are effective in maintaining the physical, chemical, and biological properties of soil. Banana cultivation requires the application of K of up to 800 kg ha^{-1} per cycle (Godefroy & Dormoy, 1988). However, several areas of banana cultivation lack manure or mineral fertilizers, resulting in K deficiency in the soil and low banana yields (Wairegi et al., 2010). Unlike other banana cultivation areas, the high K retention and supply capacity of Andosols have maintained a stable banana supply in the Kilimanjaro highlands without relying on mineral fertilizers.

Despite the synergistic effects of effective land management and the agro-ecological potential of the home garden system in the Kilimanjaro highlands, the productivity of this system relies on the C and nutrient inflow from the external ecosystems. The significance of maintaining soil fertility in external ecosystems should therefore be shared among smallholder farmers. The productivity of forests and grasslands outside home gardens ought to be managed at a community scale. Specifically, the cultivation of leguminous trees and fodder is a viable option in terms of both feed and nitrogen supply. Sustained productivity of the external environment is important for the continuation of the rural social culture of the Chagga people, where livestock holding and banana cultivation are central to their livelihoods.

6.4 Conclusion

The productivity of the Chagga home garden system in the Kilimanjaro highlands has been maintained by adapting farmland management practices to socioeconomic changes, the intensive application of livestock dung for banana cultivation, and the continuous supply of feed from outside the home gardens. The quantification of the relationship between farmland management and soil fertility conducted in this study is an essential perspective to establish appropriate soil fertility management strategies following the natural and social environment and the rural culture surrounding individual farming system arrangements to develop smallholder farming systems in SSA.

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Appendix 1

Data tables, figures, and pictures

Table A1

Soil texture and concentration of Al_o, Fe_o, and $Al_o+1/2Fe_o$ in banana gardens in the six home gardens (H1, H2, H3, H4, H5, and H6).

	Soil depth	Clay	Silt	Sand	Al_o	Fe_o	$Al_o+1/2Fe_o$
	(cm)		(%)			(g kg^{-1})	
H1	0–5	29.2	35.2	35.5	30.4	20.5	40.6
	5–20	32.4	32.9	34.7	29.7	19.8	39.6
	20–35	33.1	36.0	30.9	32.1	20.5	42.4
	35–50	27.6	41.4	31.0	37.0	22.7	48.4
	50–65	27.1	43.1	29.7	37.0	22.4	48.2
H2	0–5	41.9	39.4	18.6	37.1	16.9	45.6
	5–20	35.9	42.5	21.6	38.6	17.5	47.3
	20–35	33.1	46.0	20.9	41.5	18.7	50.9
	35–50	33.3	42.7	24.0	44.5	19.9	54.4
	50–65	36.3	44.9	18.7	51.1	20.5	61.3
H3	0–5	39.7	29.0	31.3	27.7	15.7	35.6
	5–20	31.4	36.7	31.8	27.6	16.3	35.7
	20–35	34.1	34.1	31.8	26.1	15.3	33.8
	35–50	32.5	35.4	32.2	27.2	16.0	35.2
	50–65	34.1	38.0	28.0	24.6	16.3	32.8
H4	0–5	25.5	47.2	27.4	34.9	14.5	42.1
	5–20	28.0	40.1	31.8	37.6	14.9	45.0
	20–35	35.4	39.9	24.7	38.5	14.2	45.6
	35–50	42.6	40.7	16.7	43.0	14.0	50.0
	50–65	43.4	40.1	16.6	52.6	12.3	58.7
H5	0–5	28.7	34.4	36.9	26.1	13.0	32.6
	5–20	31.3	37.9	30.8	26.0	13.0	32.5
	20–35	32.5	37.0	30.4	25.0	13.1	31.6
	35–50	32.6	36.1	31.2	26.0	14.2	33.0
	50–65	27.6	35.6	36.8	26.4	14.3	33.5
H6	0–5	38.8	34.5	26.7	24.6	12.0	30.6
	5–20	39.5	33.9	26.5	23.3	11.6	29.1
	20–35	45.2	31.1	23.8	24.8	12.1	30.9
	35–50	27.6	46.0	26.4	24.7	11.5	30.4
	50–65	38.0	34.5	27.5	25.5	11.4	31.2

Table A2

Soil texture and concentration of Al_o, Fe_o, and Al_o+1/2Fe_o in BN, MZ, and GR in H1 home garden.

	Soil depth (cm)	Clay	Silt (%)	Sand	Al_o	Fe_o (g kg^{-1})	Al_o+1/2Fe_o
BN	0–5	29.2	35.2	35.5	30.4	20.5	40.6
	5–20	32.4	32.9	34.7	29.7	19.8	39.6
	20–35	33.1	36.0	30.9	32.1	20.5	42.4
	35–50	27.6	41.4	31.0	37.0	22.7	48.4
	50–65	27.1	43.1	29.7	37.0	22.4	48.2
MZ	0–5	29.7	29.7	40.6	30.1	20.7	40.5
	5–20	29.2	31.6	39.2	29.9	20.0	39.9
	20–35	29.0	32.0	39.0	33.1	21.2	43.8
	35–50	27.8	36.0	36.2	33.8	21.5	44.5
	50–65	28.2	38.0	33.8	35.8	22.2	46.8
GR	0–5	39.8	33.6	26.6	32.4	21.7	43.3
	5–20	35.1	35.4	29.6	36.5	21.8	47.4
	20–35	28.3	39.8	31.9	38.0	25.0	50.5
	35–50	32.9	37.8	29.3	39.8	24.8	52.2
	50–65	34.4	36.2	29.4	36.5	26.9	49.9

Table A3

Soil C and nutrient stocks at different soil depths in the three land-use blocks in H1 home garden.

Soil depth	TC (Mg ha^{-1})			TN (Mg ha^{-1})			AvP (Mg ha^{-1})		
(cm)	BN	MZ	GR	BN	MZ	GR	BN	MZ	GR
0-5	22	20	19	2.1	1.9	1.9	0.12	0.05	0.03
5-20	59	57	50	5.6	5.2	4.9	0.34	0.16	0.05
20-35	55	54	44	5.2	5.0	4.4	0.24	0.13	0.05
35-50	51	50	37	4.9	4.7	3.7	0.17	0.09	0.05
50-65	58	51	30	5.5	4.7	2.9	0.11	0.08	0.06
Total	245	231	181	23.2	21.5	17.9	0.98	0.51	0.23
Soil depth	K^+ (Mg ha^{-1})			Ca^{2+} (Mg ha^{-1})			Mg^{2+} (Mg ha^{-1})		
(cm)	BN	MZ	GR	BN	MZ	GR	BN	MZ	GR
0-5	0.51	0.11	0.05	1.55	0.65	0.32	0.34	0.09	0.03
5-20	1.26	0.19	0.06	4.23	1.85	0.29	0.83	0.28	0.00
20-35	0.98	0.16	0.04	3.21	1.45	0.17	0.62	0.22	0.00
35-50	0.66	0.11	0.03	2.03	0.83	0.17	0.39	0.11	0.00
50-65	0.45	0.11	0.04	1.38	0.71	0.39	0.31	0.08	0.00
Total	3.85	0.68	0.21	12.39	5.49	1.34	2.49	0.79	0.03

Table A4

Coefficients of the estimation model of CO_2 flux at BN, MZ, and GR in H1

	n †	a ††	b †††	R^2
BN	24	1799	3.43	0.36*
MZ	23	1343	3.16	0.35*
GR	24	514	2.77	0.29*

†The number of sampling times of CO_2 efflux rate.

†† is a constant and ††† is a coefficient related to the contribution of soil moisture in Equation.

*Positive correlation at $p = .05$.

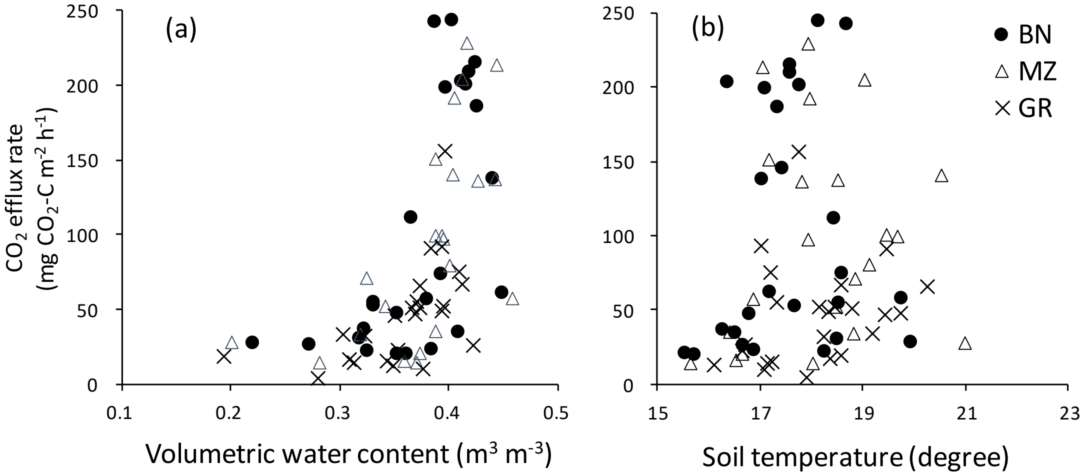


Fig. A1 Relationship between CO_2 efflux rate and (a) soil moisture and (b) soil temperature in BN, MZ, and GR in H1.

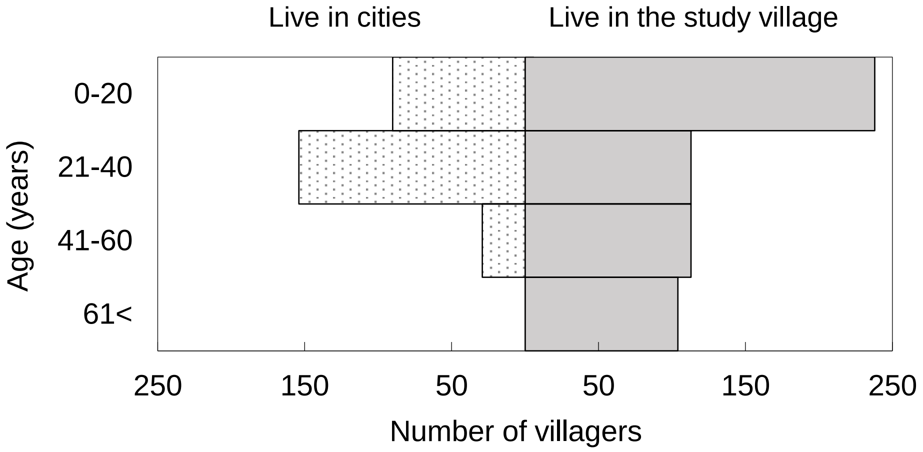


Fig. A2 Residence of family members in the study village (N = 145, 2016 survey results).

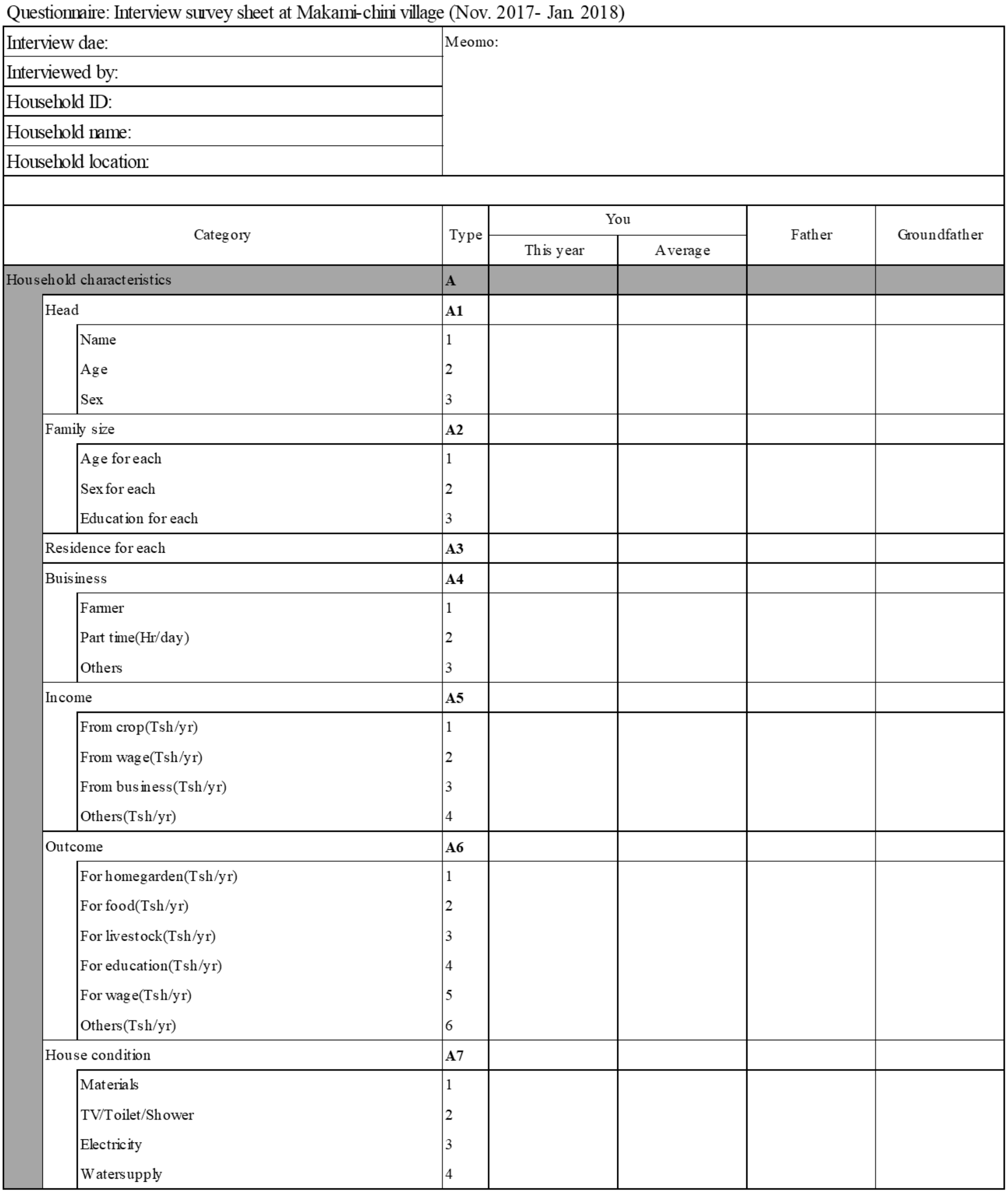
Questionnaire sheet 1.

A questionnaire about general information regarding farmland management for 145 households in the study village conducted from December 2015 to January 2016.

Questionnaire at Makami-chini village (from December 2015 to January 2016)			**Household No.**			
			1	**2**	**······**	**145**
Family structure						
Owner						
		Gender (M/F)				
		Age				
Family structure						
	Residence	Age (Number)				
	Village	0-20				
		21-40				
		41-60				
		61-				
	Town	0-20				
		21-40				
		41-60				
Crops	Type of banana	Check☑				
		muchale				
		mnyenyele				
		kisasa				
		ndishi				
		mukonoshi				
		kipungara				
		matoke				
		mulalao				
		kitarasa				
		ndizi sukari				
		Total				
	Coffee cultivation	Check☑				
		stop				
		increase				
		dectease				
		stable				
		Reason (☑)				
		Low price				
		Disease				
		Lack of farm size				
		Labor shortage				
		No market				
		Obtaining income				
		Enough farm size				
Fertilizer	Type of fertilizer	Check☑				
		samadi				
		urea				
Livestock	Type of livestock	Number				
		cow				
		goat				
		chiken				
		pig				
		sheep				
		TLU				
		TLU/ha				
Porini						
		yes/no				
		since				

Questionnaire sheet 2.

Questionnaire for the second step of the interview survey with 32 households in the study village conducted from November to December 2017 (a stratified sampling method).



Questionnaire: Interview survey sheet at Makami-chini village (Nov. 2017- Jan. 2018)

Interview dae:	Meomo:
Interviewed by:	
Household ID:	
Household name:	
Household location:	

Category			Type	You		Father	Groundfather
				This year	Average		
Household characteristics			**A**				
	Head		**A1**				
		Name	1				
		Age	2				
		Sex	3				
	Family size		**A2**				
		Age for each	1				
		Sex for each	2				
		Education for each	3				
	Residence for each		**A3**				
	Buisiness		**A4**				
		Farmer	1				
		Part time(Hr/day)	2				
		Others	3				
	Income		**A5**				
		From crop(Tsh/yr)	1				
		From wage(Tsh/yr)	2				
		From business(Tsh/yr)	3				
		Others(Tsh/yr)	4				
	Outcome		**A6**				
		For homegarden(Tsh/yr)	1				
		For food(Tsh/yr)	2				
		For livestock(Tsh/yr)	3				
		For education(Tsh/yr)	4				
		For wage(Tsh/yr)	5				
		Others(Tsh/yr)	6				
	House condition		**A7**				
		Materials	1				
		TV/Toilet/Shower	2				
		Electricity	3				
		Watersupply	4				

Questionnaire sheet 2. continued

Internal environment			**B**				
	Homegarden size		**B1**				
		Total (ha)	1				
		Banana/coffee plot (ha)	2				
		Maize plot (ha)	3				
		Grasssland (ha)	4				
	Years of cultivation		**B2**				
		Banana/coffee plot (yr)	1				
		Maize plot (yr)	2				
		Grasssland (yr)	3				
	Livestock		**B3**				
		Number of cows (improved/local)	1				
		Number of goats	2				
		Number of sheep	3				
		Number of pig	4				
		Quantity of milk produced (liter/cow)	5				
		Income from livestock	6				
	Crop		**B4**				
		Banana	1				
		Yield (kg/ha)	a				
		Selfconsume (%)	b				
		Income (Tsh/yr)	c				
		Coffee	2				
		Yield (kg/ha)	a				
		Amount of sold (kg/ha)	b				
		Income (Tsh/yr)	c				
		Maize	3				
		Yield (kg/ha)	a				
		Amount of sold (kg/ha)	b				
		Income (Tsh/yr)	c				
		Beans	4				
		Yield (kg/ha)	a				
		Amount of sold (kg/ha)	b				
		Income (Tsh/yr)	c				
	Manure		**B5**				
		Type	1				
		Quantity Applied (kg/ha)	2				
		Cost per unit (Tsh)	3				
	Chemical fertilizer		**B6**				
		Type	1				
		Quantity Applied (kg/ha)	2				
		Cost per unit (Tsh)	3				
	Mulching		**B7**				
		Type	1				
		Area (%)	2				
	Working Time		**B8**				
		Total in homegarden (Hr/day)	1				
		For livestock (Hr/day)	2				
		For coffee culticvation	3				
		For banana culticvation	4				
		Others (Hr/day)	5				

Questionnaire sheet 2. continued

Other farm	**C**				
Farm size(ha)	**C1**				
Rent or purchace price of land (Tsh)	**C2**				
Crop	**C3**				
Maize	1				
Yield (kg/ha)	a				
Self consume (%)	b				
Amount of sold (kg/ha)	c				
Income (Tsh/yr)	d				
Beans	2				
Yield (kg/ha)	a				
Self consume (%)	b				
Amount of sold(kg/ha)	c				
Income (Tsh/yr)	d				
Others	3				
Yield (kg/ha)	a				
Self consume (%)	b				
Amount of sold (kg/ha)	c				
Income (Tsh/yr)	d				
Outcome	**C4**				
Transportation fee (Tsh/yr)	1				
Cost of seed (Tsh/yr)	2				
Cost of hiring labor (Tsh/yr)	3				
Cost of Insecticide (Tsh/yr)	4				
Cost of machinery (Tsh/yr)	5				

Picture A1. Home gardens in the study village.

Picture A2. Foothill farms with maize cultivation owned by H1 owner.

Picture A3. Application of livestock dung under banana trees.

Picture A4. Agricultural practice in the study village. (a) harvest of banana, (b) cultivation of maize field, (c) harvest of coffee beans, and (d) drying of coffee beans.

Picture A5. Peeling bananas for making *Mbege* and drinking *Mbege* using a traditional cup.

Picture A6. Preparation of meals.

Picture A7. Local market near the study village and a truck for transporting bananas to urban areas.

Picture A8. Livestock (cattle and goats) and preparation of feed.

Banana leaves Banana stalks

Grasses Tree leaves Crop residues (Maize)

Picture A9. Feed supplied to livestock in the study village.

Kimalindi (AAA) *Kisasa* (AA) *Kisukari* (AAB) *Kitarasa* (AAA)

Kipungara (AAB) *Matoke* (AAA) *Mchare* (AA) *Mkonosi* (ABB)

Mrarao (AAA) *Myenyele* (AA) *Ndishi* (AAA)

Picture A10. 11 representative bananas cultivated in the home garden in the study village. Parentheses indicates genotype of banana.

Macharari *Mapoko* *Mtori*

Kibulu *Kitawa* *Mbege*

Fried banana

Picture A11. The traditional banana meals and brew of the Chagga people.

Appendix 2
Japanese abstract

キリマンジャロ高地におけるチャガホームガーデンシステムの農業生態学的研究

一ノ瀬侑理

第 1 章　序論

サブサハラアフリカにおいて急増する人口を養うために、小規模農業における食糧安全保障と土壌肥沃度管理による持続的な農業生産の実現は、喫緊の課題である。東アフリカに位置するタンザニアは、世界的に人口増加率が高い国の一つである。タンザニアの農業は、GDP と輸出総額の 1/4 を占める重要な産業で、全人口の約 65%が農業に従事し、その大部分が小規模農業を営んでいる。そのため、タンザニアにおける小規模農業の活性化は、当地域の食料と雇用を安定的に確保する上で非常に重要となる。タンザニア北東部に位置するキリマンジャロ山の南東斜面は、タンザニアの中でも特に人口密度の高い地域であると同時に、農業活動が盛んな地域として知られる。キリマンジャロ高地では、チャガと呼ばれる人々が作物生産と家畜飼育を中心としたホームガーデンシステムを 100 年以上に渡り営んできた。本研究では、チャガのホームガーデンシステムの生産性が長年に渡り維持されてきた仕組みを理解することを目的として、小規模農家による農地管理の適応戦略の解明、ホームガーデンにおける家畜と農地利用が土壌肥沃度に及ぼす影響の解明、ホームガーデンシステムの炭素・養分収支の解明、に取り組んだ。

第 2 章　研究対象地の概要

本研究は、キリマンジャロ山南東斜面の標高 1,600 m に位置するマカミチーニ村のホームガーデンを研究対象とした。調査地の年平均気温は 21℃、年平均降水量は 1,500－2,000 mm で 1 年に 2 回の雨季があり、土壌は Andosols に分類される。調査村は 307 世帯で構成され、村民の大部分は農業を生業としている。ホームガーデンにおける栽培作物は、当地域の主食であるバナナと換金作物であるコーヒーを中心に、その他にトウモロコシ、ヤムイモ、マメ類、牧草が栽培され、農地は栽培作物によって異なる管理が行われている。ホームガーデン内ではウシやヤギなどの家畜が舎畜され、家畜フンを農地に施用する一方で、農地で生産された作物残渣や牧草を家畜の餌として供給する。本研究では、145 世帯を対象とした参与観察と聞き取り調査と、代表 6 世帯を対象とした物質動態調査を、2015 年から 2018 年にかけて行った。

第 3 章　キリマンジャロ山チャガによる生計維持のための農地管理の適応戦略

近年のタンザニア国における社会的・経済的変化に対するキリマンジャロ山小規模農業の農地管理の適応戦略を明らかにするために、145 世帯を対象に現地参与観察とインタビュー調査を

行った。その結果、ホームガーデンは全世帯で保有されていたが、その面積は親の代の半分以下となった世帯が多く、麓の畑は約半分の世帯でのみ所有されていた。また、世界市場のコーヒー価格の下落に伴い、コーヒーの収益性が減少していた。その対策として農民は、ホームガーデン内におけるコーヒー栽培を縮小させる一方で、伝統的主食であるバナナ栽培と新たな食文化として台頭するトウモロコシ栽培を拡大させていた。バナナ栽培の拡大は、主食の確保に加えて、近年の交通インフラの発達によりバナナ市場が拡大し、換金作物としてのバナナの価値が高まっていることが要因と考えられた。つまり、ホームガーデンにおける栽培作物の選定は、近年の人口増加による農地の細分化により、限られた農地面積で食料生産と収入の安定化を達成するための農民の戦略によるものと考えられた。一方で、古くから交通の要衝であるキリマンジャロ山に持ち込まれた多様なバナナを用いたバナナ食文化は今なお継承されており、使途の異なる 11 種のバナナが栽培されていることが遺伝型解析によって明らかとなった。以上より、農地面積の縮小や作物の市場価値の変化、また食生活の変化に対して、農民は農業システムを柔軟に変容させることで適応してきたことが示された。

第 4 章　キリマンジャロ山の伝統的なホームガーデンにおける家畜と農地利用の中心的役割

世帯間の家畜保有の違いと農地内土地管理法の違いが、ホームガーデン内の土壌肥沃度に及ぼす影響を解明することを目的とし、家畜密度の異なる 6 世帯のホームガーデンと、代表 1 世帯のホームガーデン内農地における 3 つの異なる栽培地（バナナ栽培地、トウモロコシ栽培地、牧草地）を対象に、土壌断面（0－5、5－20、20－35、35－50、50－65 cm 深）における炭素および養分の濃度と蓄積量を調べた。その結果、各世帯の家畜密度と土壌断面内の養分濃度（陽イオン交換容量、可給態リン、全交換性陽イオン）および pH との間に有意な正の相関が見られ、家畜フン施用による土壌肥沃度の向上効果が示された。一方で、これらの元素と比較し、家畜密度は土壌炭素濃度と土壌窒素濃度と弱い正の相関を示した。これは有機物分解による炭素損失量が大きいこと、また、作物吸収などを通した土壌からの窒素損失が影響したためだと考えられた。ホームガーデン内では、最も家畜フンが施用されるバナナ栽培地の土壌断面全体における土壌炭素・養分蓄積量（全窒素、可給態リン、交換性塩基）が 3 つの栽培地の中で最も高くなった。すなわち、家畜フンの施用とその配分方法が、当地域のホームガーデンの土壌肥沃度を維持するうえで重要な農地管理であることがわかった。

第 5 章　キリマンジャロ高地のチャガホームガーデンシステムにおける炭素･養分収支

小規模農家による農地管理が、ホームガーデンシステムの炭素・養分収支に与える影響を評価した。ホームガーデン内の異なる 3 つの栽培地、バナナ栽培地、トウモロコシ栽培地、草地における土壌炭素、窒素、リン、カリウム、カルシウム、マグネシウム収支の算出と、ホームガーデンシステム全体における内部循環と外部流出入フローを定量した。その結果、バナナ栽培地では家畜フンを集中的に施用と攪乱の少ない多年生のバナナ栽培を組み合わせることで、土壌炭素収支がプラスとなったと考えられた。土壌窒素・カリウム収支はマイナスとなったが、

これは土壌断面内（0－65 cm 深）における窒素・カリウム蓄積量に対して非常に小さい値となった。窒素とカリウムの土壌からの損失は、エサと作物の採取による持ち出し量が最も大きく、溶脱の影響は小さかった。これは有機態窒素を多く含む家畜フン施用と Andosols による高いカリウム保持・供給能による効果だと考えられた。すなわち、ホームガーデンにおける家畜フン施用とバナナ栽培による土壌肥沃度管理が、降雨量が多く Andosols の広がる当地域において炭素蓄積を促進し、養分損失を抑制する効果的な管理方法であることがわかった。一方、トウモロコシ栽培地では有機物分解量が多く、炭素収支がマイナスとなった。牧草地では家畜フンの施用がない一方、継続的にエサが採取されることで、全元素の収支がマイナスとなった。また本システムでは家畜に供給される炭素・養分のうち 33－47%は家庭菜園の外から供給されており、ホームガーデン外における継続的なエサの確保がシステムの生産性を維持する上で重要であることがわかった。

第 6 章　考察および結論

本研究では、チャガのホームガーデンシステムにおける農地管理戦略と土壌肥沃度の関係について明らかにした。チャガの農地管理戦略では、世帯あたりの農地面積が減少している現在、バナナの食料と収入源としてのマルチな役割、コーヒーの収益性の減少、トウモロコシの主食としての生計における重要性を背景に、限られた農地から食料と収益を確保する方法として、ホームガーデン内におけるコーヒー栽培の減少、バナナ栽培の維持と拡大、トウモロコシ栽培の開始が実践されたと考えられた。土壌肥沃度管理においては、家畜フンを唯一の肥料とする本システムにおいて、家畜密度が土壌肥沃度を規定していることがわかった。また、家畜フンを集中的にバナナ栽培地に施用することは、キリマンジャロ高地において効果的な土壌肥沃度管理方法だと考えられ、バナナを生活の中心とするチャガの文化社会環境と合致した農地管理戦略であると考えられた。これまでシステムの生産性は、システム内の資源循環により維持されていると考えられていたが、実際は家畜のエサの供給を通したシステム外部からの炭素・養分の流入がシステムの生産性を維持する上で重要な役割を果たすことがわかった。以上の結果より、キリマンジャロ高地におけるチャガのホームガーデンシステムの生産性は、小規模農家が社会経済変化に対し農地管理戦略を柔軟に適応させ、ホームガーデンシステム内においてバナナ栽培へ集中的に家畜フンを施用することに加えて、システムの外から継続的にエサを確保することにより、維持されているということが明らかとなった。本研究で取り組んだ「農地管理戦略と土壌肥沃度の関係を定量化する」という研究アプローチは、多様な農業生態系が広がる SSA 小規模農業の活性化を目指す上で、個々のシステムを取り巻く自然・社会環境・農村文化に応じた適切な土壌肥沃度管理を構築するための重要な視点となる。

Publication

Chapter 3

Ichinose, Y., Nishigaki, T., Kilasara, M., and Funakawa, S. 2020. Central roles of livestock and land-use in soil fertility of traditional homegardens on Mount Kilimanjaro. *Agroforestry Systems* 94. 1–14. doi: 10.1007/s10457-019-00357-9

Chapter 4

Ichinose, Y., Higuchi, H., Kubo, R., Nishigaki, T., Kilasara, M., Shinjo, H., and Funakawa, S. 2020. Adaptation of farmland management strategies to maintain livelihood by the Chagga people in the Kilimanjaro highlands. *Agricultural Systems* 181, 102829. doi: 10.1016/j.agsy.2020.102829

Chapter 5

Ichinose, Y., Nishigaki, T., Shibata, M., Kilasara, M., Shinjo, H., and Funakawa, S. Carbon and nutrients budget of the Chagga home garden system in the Kilimanjaro highlands. (in preparation for submitting to *Agricultural Systems*)