Dynamics of Soil Organic Matter under Slash-and-Burn Agriculture in a Semiarid Woodland of Zambia

Kaori Ando

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Kaori Ando

Contents

List of Tables

List of Figures

Chapter 1

Introduction

1.1 Study background

1.1.1. Problems of agricultural management in semiarid tropics of Africa

Soil organic matter (SOM) is important to sustain crop productivity for famer in semiarid tropics of Africa who use little fertilizer and rely on the nutrient released from SOM (Lal, 1997; Mapfumo et al., 2007). The SOM which decreases during clearing and cropping has been restored during fallow in slash-and-burn agriculture in the Africa (Nandwa, 2001). However, conversion of woodland to cropland followed by shortening fallow length has been increasing due to high land use pressure, which may cause the decrease in SOM (Nandwa, 2001; Chirwa et al., 2004; Mapanda et al., 2013). Therefore, the effect of the conversion to cropland and shortened fallow period on SOM is needed to be elucidated for evaluation and improvement of soil fertility (Nandwa, 2001; Palm et al., 2001).

1.1.2. Impacts of slash-and-burn practice on soil organic matter in Eastern Province, Zambia

When woodland is cleared for cropland, various slash-and-burn practices are used, based on the aboveground biomass present in an area, resulting in varied responses. In tropical humid regions such as Southeast Asia, South America and Central Africa, with aboveground biomass of about 150–350 Mg ha^{-1} (Hertel et al., 2009), slashed trees cover an entire cleared area to be burned (Rasul and Thapa, 2003). In contrast, the aboveground biomass in the semiarid tropics covered by miombo woodland composed of emergent tree and bush trees was only 69 Mg ha^{-1} (Chidumayo, 1997). In Northern Province, Zambia, not only trees slashed in a cleared field but also branches collected from surrounding woodland are burned to compensate for the low levels of biomass. Then they are piled to cover the entire cleared field to be burned (Strømgaard, 1984). In Eastern Province, trees are cut only within the field being opened, and the cut trees are collected and piled only in part of the field because of the low levels of biomass. Therefore, only the spots with the tree piles are burned and the remaining cleared spots without piles are not burned.

Traditionally, most of the piles were composed of the emergent trees. However, shorter fallow periods caused decrease in emergent tree biomass recently, and the trees piles composed of bush trees in turn has increased. Therefore, two kinds of tree piles, such as emergent and bush trees piles, could be present simultaneously within the cleared field (Fig. 1.1). This recent practice may increase the spatial variability of the extents of burning with these mosaic spots of unburned and burned with two levels of biomass. The extents of burning or, fire intensity, which were determined by the maximum temperature and the duration of burning (Hatten and Zabowski, 2009), affects the extent of SOM degradation and nutrient release (Ellingson et al., 2000; Giardina et al., 2000a; Tanaka et al., 2004). Therefore, it is essential to reveal the spatial variability of SOM and nutrient release immediately after burning (Fig. 1.1).

1.1.3. Changes of soil organic matter during cropping and fallow

The decline of SOM during cropping after clearing and burning has been attributed to various factors; the increase in mineralization of SOM via high microbial activity (Tinker et al., 1996; Jobbagy and Jackson, 2000), incorporation of plant materials (Balesdent et al., 1998; Huggins et al., 1998) and breakdown of soil aggregation by plowing (Six et al., 2002), and decrease in the amount of input returned to soil (Huggins et al., 1998; Paustian et al., 2000; Norton et al., 2012). Particularly, the amount of input may decrease with increase in cropping period (Tian et al, 2005) but the rate of the decrease may be different among the spots with different fire intensity. Additionally, the composition of input may also change in response to the decrease in tree coppicing ability with increase in cropping period and/or fire intensity (Luoga et al., 2004), which may affect decomposition rate. Therefore, the decrease process of SOM during cropping may be different among the spots unburned and burned with emergent and bush tree piles (Fig 1.1).

It should be concerned that those different extents of decrease in SOM during cropping with different fire intensity could be restored during the recent shortened fallow after cropping (Fig 1.1). Restoration of SOM during fallow is attributed to increase in litter returned to soil (Funakawa et al., 2006; Adiku et al., 2008), and decrease in decomposition of SOM with leaving plant litter on soil surface (Huggins et al., 1998; Ouattara et al., 2006). Several studies have claimed that the short fallow was not enough to recover the decrease in SOM by cropping or burning (Brady, 1996; Mertz, 2002; Hauser et al., 2006). However, it depends on the extent of decrease in SOM and vegetation during cropping before fallow (Mobbs and Cannell, 1995; Hauser et al., 2006). Hence, evaluation of restoration of SOM during fallow is needed to consider not only fallow period but also the cropping period and fire intensity before fallow (Fig 1.1). However, little has been reported on the evaluation of changes in SOM stock during different cropping period followed by short fallow under the slash-and-burn agriculture, with the changes in composition and amount of input.

It is important to evaluate cropping and short fallow rotation in terms of carbon (C) and nitrogen (N) contents of labile soil fraction and the C and N budget estimated by input to soil and output from soil. Labile soil fraction, such as coarse organic matter (COM; >2000 μm) and particulate organic matter (POM 53–2000 μm) are sensitive enough to detect changes of land use or changes of input, and easy to measure (Cambardella and Elliot et al., 1992; Mapfumo et al., 2007). On the other hand, the C and N budgets are time consuming method but could detect even small changes of C and N which could not find by direct measurement of soil stock of C and N because of heterogeneous in soil itself. Therefore, the validation of changes in C and N contents of SOM by input to soil and output from soil is useful for the establishment of well-balanced cropping and short fallow rotation (Paustian et al., 2000).

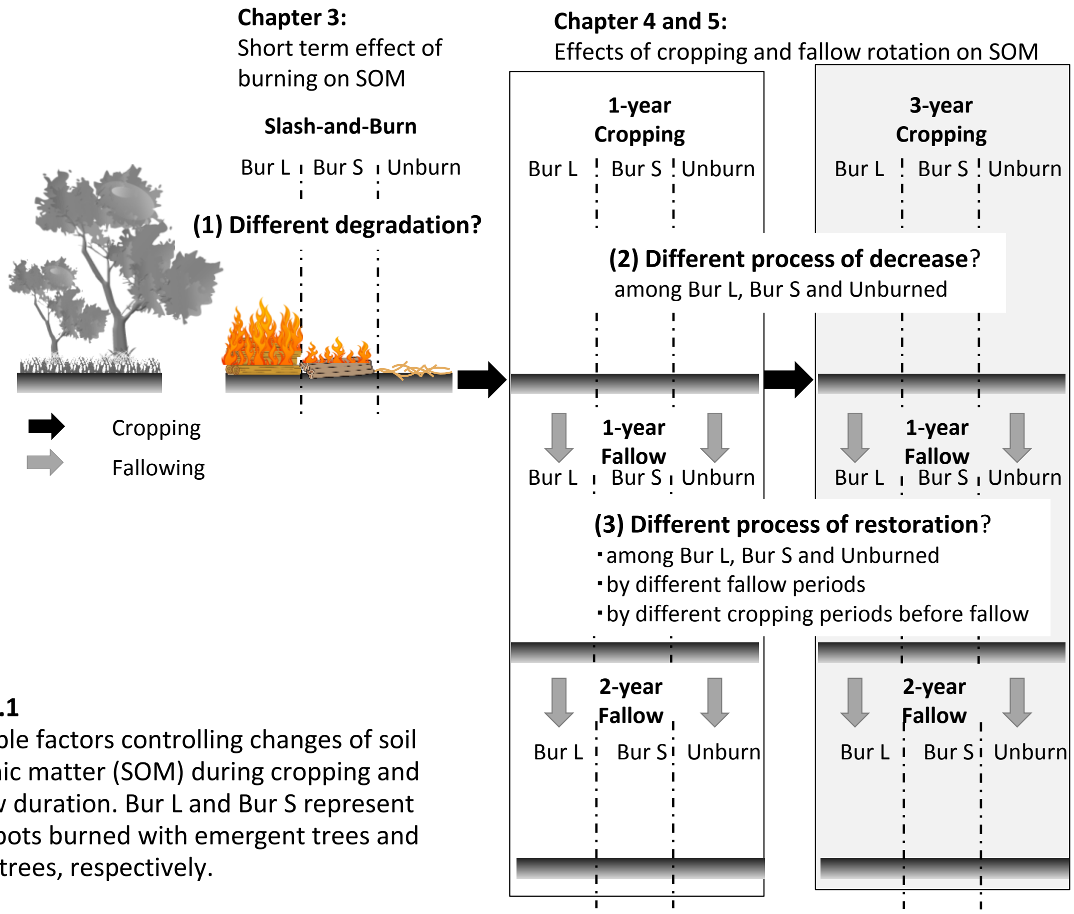

Fig. 1.1
Possible factors controlling changes of soil organic matter (SOM) during cropping and fallow duration. Bur L and Bur S represent the spots burned with emergent trees and bush trees, respectively.

1.2. Study objectives

The objectives of this study were (1) to evaluate the effects of fire intensity on SOM and nutrient release immediately after burning (Chapter 3), and (2) to evaluate the changes of C and N contents in COM and POM under different cropping period followed by short fallow with reference to the changes of the composition and the amount of input (Chapter 4), (3) to estimate C and N budget during cropping and short fallow rotation from input and output flow (Chapter 5). Finally, the effects of cropping and short fallow rotation on SOM through changes of vegetation considering the spatial variability of unburned spots, burned spots with emergent and bush trees is discussed (Chapter 6).

Chapter 2

Description of study site

2.1 General characteristics of the study site

The study site is located in a village in Eastern Province of Zambia in southern Africa (Fig. 2.1: 14°08'S, 31°43'E; 890 m above sea level). The climate has a unimodal distribution of annual rainfall with a rainy season from November to April, and a dry season in the remaining months (Fig. 2.2). The climatic conditions in the region has variance of rainfall year by year with frequent droughts over recent a few decades (Lobell et al., 2008), from 597 mm to 1206 mm. During the experimental period, the mean annual air temperature was 24°C from 2008 to 2012 and annual rainfall in the rainy season was 762 mm in 2008/2009, 986 mm in 2009/2010, 1019 mm in 2010/2011 and 806 mm in 2011/2012. In the study site covered by miombo woodland composed of emergent trees and bush trees, aboveground biomass was 38.3 Mg ha^{-1}, much lower than that reported by Chidumayo (1997). This suggests that emergent trees have been lost under serious land use pressure in the region. The vegetation type of this woodland is classified as the eastern dry miombo (Chidumayo, 1997), dominated by *Brachystegia manga*, *Julbernardia globiflora* and *Diplorhynchus condylocarpon*. The soil was classified as Typic Plinthustalfs (Fig. 2.3: Soil Survey Staff, 2006). The soil at the depth of 0–15 cm in long fallow had a pH of 6.8 with water to soil ratio of 5, soil texture of sandy loam containing 66.5% sand, 19.6% silt and 13.6% clay, total C of 1.30% and total N of 0.082% (Table 2.1).

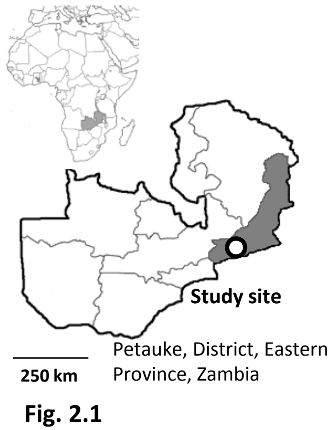

Fig. 2.1
Location of study site

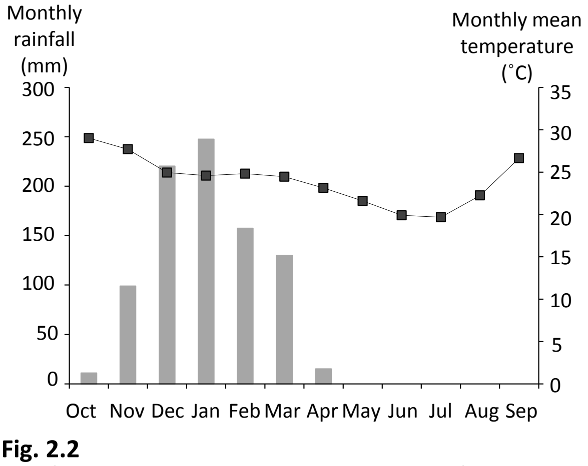

Fig. 2.2
Rainfall and monthly mean temperature of study site

Fig. 2.3
Picture of soil profile

Table 2.1
Soil characteristics at the depth of 0-15cm at the start of cultivation

Total C (g C kg^{-1} soil)	13.0
Total N (g N kg^{-1} soil)	0.8
C/N	15.9
pH (H_2O)	6.8
Soil texture (%)	
Clay	66.5
Silt	19.6
Sand	13.6
Bulk density (Mg m^{-3})	1.3

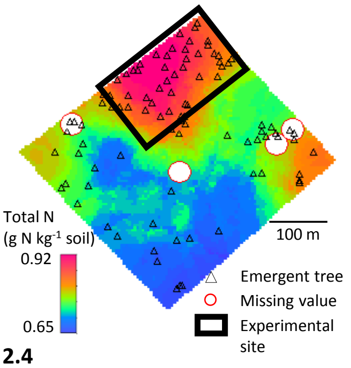

Fig. 2.4
Map of total N content at the depth of 0–5 cm and location of emergent trees in 400×400 m of experimental site inside the village

Villagers in Eastern Province, Zambia, clear and prepare land for cropping conventionally as follows. Trees are cut only within the field being opened, and the cut trees are collected and piled only in a part of the field because of the low biomass. Therefore, only the spots with the tree piles are burned; the remaining cleared spots without piles are not burned. The piles are left to dry during the dry season and burned at the end of dry season. The burned spots are not plowed during the first year following traditional local farming practices, while cleared spots without piles are plowed prior to burning to prevent them from burning.

2.2. Description of experimental plot

The woodland site (100 × 230 m) was selected in a flat and uniform place in terms of C and N contents of SOM and vegetation (Fig. 2.4). Land clearing and preparation for the experiment was carried out according to the conventional practice as already described. A part of the experiment site was opened by slash-and-burn practice every year from October 2007 to October 2010 (Fig. 2.5). After land clearing, three seeds of maize (*Zea mays*) were planted in each hole with plant density of 1 × 1 m grid at the beginning of December. Weeds were removed about three and six weeks after planting. Then some of the plots were returned to fallow after cropping for 1 to 3 years as shown in Fig. 2.5. Each plot with three replication had spots unburned and burned with emergent and bush tree piles (Fig. 2.6).

2.2.1. Slash-and-burn practice

After trees were cut within each field being opened, bush trees and emergent trees were piled separately in different parts of the experimental field (Fig. 2.6). Trees with a diameter at breast height (DBH) smaller than 27 cm are referred to as “small trees” or bush trees; trees with a DBH larger than 27 cm as “large trees” or emergent trees, hereinafter. The remaining spots without piles were plowed prior to burning. Then, the plots were divided into three treatment areas (Fig. 2.6).

1) Unburned: consisting of unburned spots after clearing (85.6% of total field)

2) Bur S: spots burned with piles of small trees (7.5% of total field)

3) Bur L: spots burned with piles of large trees (6.9% of total field)

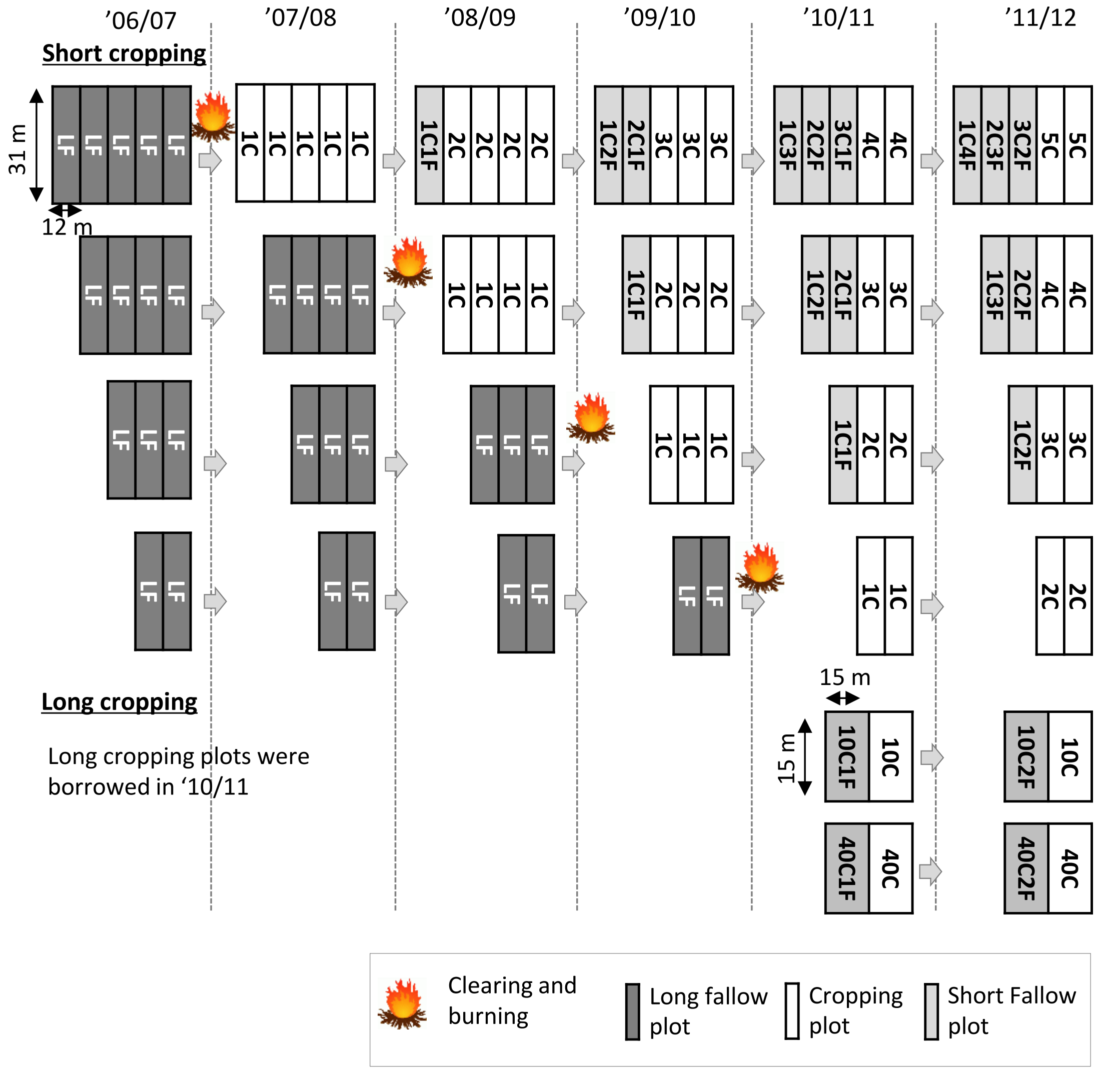

Fig. 2.5
Schematic diagram on history of experimental treatments
LF represents long fallow, C represents cropping and F represents fallow. Values followed by C or F shows the period of cropping or fallow, respectively. For example, 1C1F represents 1-year cropping followed by 1-year fallow. In the experimental site, the plots with these treatments were arranged with three replicates as shown in Fig. 2.6.

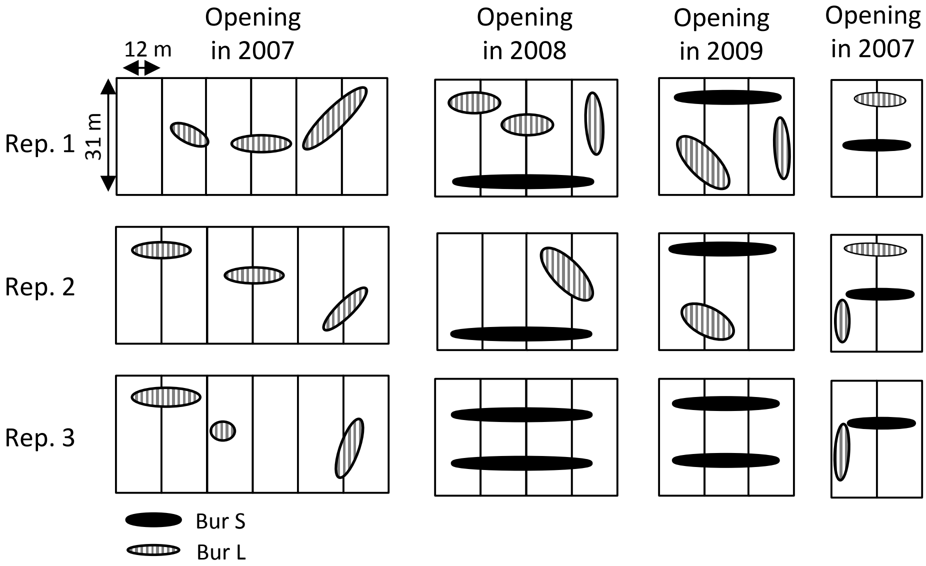

Fig. 2.6
Design of plots with three replicates and the spots burned with emergent trees (Bur L) and bush trees (Bur S). Rep. represents replicate of treatment.

2.2.2. Cropping and short fallow rotation

To establish plots of cropping and short fallow rotation for the experiment in Chapter 4 and 5, the site opened by the slash-and-burn practice was divided into plots (12 × 31 m) with three replicates. After the 1-year cropping, some of the plots continued cropping, and the other returned to fallow every year according to Fig. 2.5. The treatments of 1C, 2C, 3C, 4C and 5C represent cropping for 1, 2, 3, 4 and 5 years after clearing long fallow (LF) to cropland (C). The treatments of 1C1F, 1C2F, 1C3F and 1C4F mean short fallow (F) for 1, 2, 3 and 4 years after 1-year cropping, respectively. The treatments of 2C1F, 2C2F and 2C3F represent fallow for 1, 2 and 3 years, respectively after 2-year cropping. The plots of 3C1F and 3C2F represent fallow for 1 and 2 year, respectively after 3-year cropping. In 2011/2012, no plot was returned to fallow. Each plot has the spots of Unburned, Bur L and Bur S according to Fig. 2.6. A 20 × 30 m LF plot was also marked inside the experimental site.

For establishing the plots with long cropping and short fallow rotation, three fields with 10-year cropping and two fields with 40-year cropping were selected in the village on which fertilizer had never been applied. The plots were divided into cropping and fallow treatments (15 × 15 m) in October 2010. A LF plot was also established close to each long cropping plot.

Chapter 3

Short term effects of fire intensity on soil organic matter and nutrient release after slash-and-burn

3.1. General

Soil organic matter (SOM) is an essential resource of an available form of nutrients for plants (Cambardella and Elliot, 1992). In the semiarid tropics of southern Africa, recent rapid conversion of woodland to cropland may cause a decrease in SOM (Jaiyeoba, 2003; Mapanda et al., 2013; Okore et al., 2007; Walker and Desanker, 2004).

According to slash-and-burn practice in Eastern Province, Zambia, cut trees are piled and burned in only a part of the cleared fields because inherently low tree biomass could not burn the entire field (refer to Chapter 1). Due to the recent decrease in emergent trees, not only emergent tree piles but also bush tree piles may exist. Therefore, the spots with different extents of burning exist in the cleared field.

Burning consumes and alters SOM and is followed by the release of available nutrients. The extent of SOM degradation and nutrient release depends on fire intensity which increases as the amount of biomass burned per unit area increases. In laboratory experiments, the amount of SOM remaining after a fire decreased with an increase in fire intensity (Dunn et al., 1979). However, no coherent results related to the changes of SOM have been observed in field studies of slash-and-burn agriculture. This occurs because almost all the burned sites had different soil textures and soil moisture content that affected the change in SOM during burning (Giardina et al., 2000b; Kauffman et al., 1993, 1995; Kendawang et al., 2004, 2005; Strømgaad, 1992; Tanaka et al., 2004). For instance, Giardina et al. (2000b) reported that the amount of SOM decreased with an increase in fire intensity in a sandy loam soil with low soil moisture content; Strømgaad (1992) showed that levels of SOM increased with any fire intensity in sandy soil with low moisture content. The different changes in SOM quality caused by different soil heating affected the release of labile C and available nutrients (Ellingson et al., 2000; Giardina et al., 2000b; Strømgaad, 1992; Tanaka et al., 2001, 2004).

Thus, *in situ* evaluation of changes in SOM after burning is needed in Eastern Province, Zambia. However, few studies in Eastern Province have analyzed *in situ* changes of SOM and labile C as well as available nutrients considering variations in fire intensity inside cleared fields (Chidumayo and Kwibisa, 2003). Although determining fire intensity by measuring both maximum and temporal change of soil temperature during burning provides valuable information (Hatten and Zabowski, 2009), most past studies that determined fire intensity have been based on only maximum temperature (Giardina et al., 2000a; Kauffman et al., 1993; Kendawang et al., 2004, 2005; Strømgaad, 1992; Tanaka et al., 2001, 2004). Therefore, the objectives of this chapter were to evaluate *in situ* changes of SOM, labile C and available nutrients immediately after burning in the entire cleared field including unburned spots, and burned spots with emergent and bush tree piles, and revealed the relationship between degradation of SOM and fire intensity determined by maximum soil temperature and duration of burning.

3.2. Materials and methods

3.2.1. Experimental design

Bush trees are referred to as small trees; emergent trees as large trees. Treatments immediately after burning at spots unburned (Unburned), and at spots burned with large trees (Bur L) and with small trees (Bur S) were established in October 2008, 2009 and 2010 as described in Chapter 2 (Fig. 2.5). The burned spots accounted for only 6.9% (Bur L) and 7.5% (Bur S) of the total area of fields (Fig. 3.1, Table 3.1).

1) Unburned: consisting of unburned spots
2) Bur S: spots burned with piles of small trees
3) Bur L: spots burned with piles of large trees

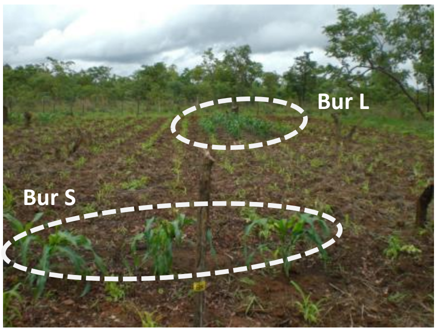

Fig. 3.1
Picture of the piles with emergent tree (Bur L) and bush tree (Bur S) at the 21 days after planting

3.2.2. Soil and ash sampling

In October 2008, soils from Unburned were sampled at the depth of 0–15 cm by a 0.3 L soil core because the soil at this depth was mixed uniformly by plowing. Samples collected at nine locations in each treatment were thoroughly mixed to make a composite sample. In October 2008 and 2009, ash samples were collected with an 18.5

Table 3.1
Characteristics of burned trees and burned spots in 2008–2010

	Tree height	Tree DBH†	Tree biomass	Burned area per total cleared area	Burned biomass per area burned
	(m)	(cm)	(Mg ha^{-1})	(%)	(Mg ha^{-1})
Bur L	18.9 ± 1.0	43.1 ± 1.3	29.3 ± 4.8	6.9 ± 0.5	209.4 ± 20.1
Bur S	3.5 ± 0.1	3.1 ± 0.2	9.0 ± 1.4	7.5 ± 1.1	84.5 ± 13.4

Values are mean ± standard error (n = 9). † DBH is diameter of breast height. The tree biomass (Y) was estimated by the allometric equation of Chidumayo (1997). The equation for Bur L was Y = 13.67 × DBH + 7.48 × height–193.2 and Bur S was Y = 0.99 × DBH–0.61. Unite of DBH is cm. Height represents tree height (m). Bur L is the spots burned with large tree piles (DBH > 27 cm) and Bur S is the spots burned with small tree piles (DBH < 27 cm).

×18.5 cm quadrate for the both Bur S and Bur L. The ash was defined here as all the residual materials on the ground after burning the tree piles (Giardina et al., 2000b). Then, soil samples were collected separately from depths of 0–5, 5–10 and 10–15 cm by a 0.1 L soil core because those areas had not been plowed. Ash and soil samples were collected at each depth from nine and three locations in each treatment for Bur L and Bur S, respectively, and were mixed to make a composite sample. The composite samples were sieved through a 2 mm mesh after removing visible plant debris, then immediately transported to the laboratory and refrigerated at 4°C until testing.

3.2.3. Determination of fire intensity

Fire intensity was determined using maximum soil temperature and duration of the soil heating. The maximum soil temperature was determined by thermo-crayons (Thermo-Crayon M, Nichiyu Giken Kogyo Co., Ltd., Japan) at the Bur L and Bur S in 2008. The crayons were whittled and put between stainless steel nuts. Crayons with melting points of 50, 100, 200, 300, 460, 615, 765 and 885°C were buried at depths of 0, 5, 10 and 15 cm. Temporal change in soil temperature during burning was measured at depths of 1, 3, 5, 10 and 15 cm at the Bur L and Bur S by digital thermometers in 2010 (CT-2310, Custom Corp., Japan). The temperature was recorded every 10 or 15 minutes during the first 7 hours after ignition and every 0.5–2 hours until the temperature equaled annual average soil temperature. All parts of the thermometer and cables were buried to protect them from fire. Both of thermo-crayons and digital thermometer measured the soil temperatures with three replications. The temperature during burning could be considered equal in 2008, 2009 and 2010 because soil water content at the end of dry season was always less than 2% for all three years and the amount of burned biomass per burned unit area did not differ significantly.

3.2.4. Physicochemical analysis of soil and ash

Soil bulk density was determined by oven drying soil for 24 hours. The dry weight of ash was measured after oven-drying soil for 24 hours, and after grinding soil prior to analysis. Soil pH (H_2O) was measured with a soil to water ratio of 1:5. The total C and total N content of the soil and ash were analyzed by the dry combustion method with a NC analyzer (Vario Max CHN; Elementar, Germany). Available P was extracted by the Bray-1 method (Bray and Kurtz, 1945) and was measured with the molybdenum blue method. Exchangeable Ca, Mg, K and Na were extracted with 1 mol L^{-1} ammonium acetate at pH 7. Total P, Mg, Ca, K and Na in ash were determined by wet digestion with nitric and sulfuric acid. The Mg and Ca content in the extracts and digested solutions were determined by atomic absorption spectrometry, the K and Na contents by flame photometry (A-A-640, Shimadzu, Japan), and the P contents by the molybdenum blue method.

3.2.5. Carbon and N mineralization

Carbon mineralization was determined by the aerobic incubation method (Kendawang et al., 2004). The samples were incubated at 30°C for 56 days. The CO_2 collected by the alkali trap was sampled after 3, 7, 14, 28, 42 and 56 days of incubation and measured by an automatic titrimetric analyzer (COM-1600, Hiranuma Sangyo Co., Ltd., Japan).

Nitrogen mineralization was determined by the aerobic incubation method (Funakawa et al., 2006). After incubation at 30°C for 3, 7, 14, 28, 42 and 56 days, the samples were extracted with 2 mol L^{-1} KCl. The NH_4–N in the extract was determined by the modified indophenol blue method (Rhine et al., 1998) and the NO_3–N in the extract was determined by the Griess–Ilosvay method (Mulvaney, 1996) after reduction to NO_2–N with Cd.

The daily rate of C and N mineralization for 3 days and 56 days was calculated by Equation (3.1):

$$Min_{rate} = \frac{Min}{D} \qquad (3.1)$$

where Min_{rate} is the daily rate of C or N mineralization (mg (C or N) kg $^{-1}$ day^{-1}), Min is the amount of C or N mineralization at 3 day and 56 day (the entire period), and D was the each duration of the mineralization.

3.2.6. Plant sampling and analysis

The dry weight of woody biomass was estimated from an allometric equation reported by Chidumayo (1997). Maize stover and grain were collected at three hills for each treatment in April 2009 and 2010. At weeding and harvesting times, aboveground parts of woody and herbaceous weeds were collected separately from three 1 × 1 m quadrates for each treatment. The samples were weighed after drying at 70°C for 48 h.

3.2.7. Statistical analyses

All statistical analyses were performed with Sigma plot 11.0 (SYSTAT Software Inc., San Jose, CA, USA). All data were expressed on a dry-weight basis (mean ± standard error). One-way analysis of variance (ANOVA) was used to detect significant differences between variables. When ANOVA indicated a significant difference, mean comparisons were performed with Tukey–Kramer multiple comparison test. Soils from the Unburned had been plowed causing them to be uniform at a depth of 0–15 cm. Thus, the mineralization rate in Unburned soil at a depth of 0–15 cm was compared with those in Bur L and Bur S at each depth (0–5, 5–10 and 10–15 cm). Comparing the mass data between Unburned and Burned treatments, the values for 0–5 cm, 5–10 cm and 10–15 cm was summed in each treatment of Bur L and Bur S after converting the unit of the values from concentration (mg kg^{-1}) to mass (Mg ha^{-1} or kg ha^{-1}).

3.3. Results

3.3.1. Biomass of burned trees

Table 3.1 shows characteristics of the burned trees and burned spots through the experiment. The burned area covered 6.9% and 7.5% of the total cleared area in Bur L and Bur S, respectively (Fig. 3.1), and burned biomass per unit burned area of Bur L and Bur S was 209.4 ± 20.1 Mg ha^{-1} and 84.5 ± 13.4 Mg ha^{-1}, respectively. As indicated by the small values of standard error, the burned biomass per unit area was not different significantly among the three experimental years.

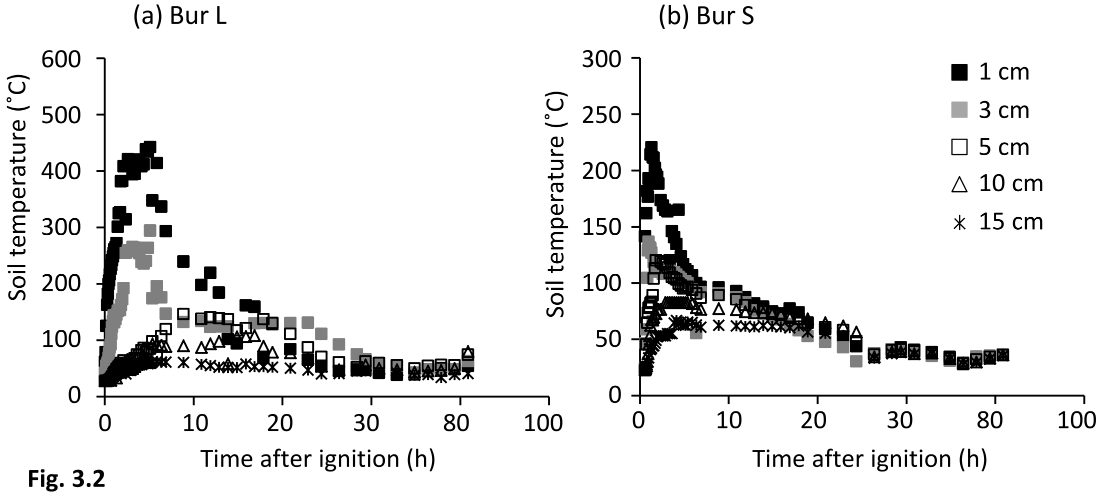

Fig. 3.2
Soil temperature during burning at depths of 1, 3, 5, 10, and 15 cm at Bur L and Bur S in 2010

3.3.2. Fire intensity

Table 3.2 shows the maximum soil temperature during burning in 2008. In Bur L, the temperature rose to 300 – 460°C and 100 – 200°C, at depths 5 and 10 cm, respectively. In Bur S, the temperature rose to only 50 – 100 °C and 50°C at depths of 5 and 10 cm, respectively. This observation was followed by the temporal change in soil temperature in 2010 (Fig. 3.2). The average of maximum temperature was 442, 294, 159, 108 and 62°C at depths of 1, 3, 5, 10 and 15 cm in Bur L, and was 220, 136, 110, 82 and 62°C at depths of 1, 3, 5, 10 and 15 cm in Bur S, respectively. Soil temperature above 80°C at 3 cm deep lasted for 56 hours in Bur L, but for only 9 hours in Bur S. Thus, burning was more intense in Bur L than that in Bur S in terms of maximum temperature, and the depth and duration of soil heating.

Table 3.2
Maximum soil temperature during burning measured by Thermo-crayon in 2008

	Maximum soil temperature (°C)	
Depth (cm)	Bur L	Bur S
0	460 – 600	460
5	300 – 460	50 – 100
10	100 – 200	50
15	50	50

Values shows the temperature of Thermo-crayon-melting point (*n* = 3).

3.3.3. Soil and ash physicochemical properties

The soil water content before burning was 1.77 ± 0.03% in all the treatments. Table 3.3 shows the soil and ash physiochemical properties after applying the treatments. Total C at 0–15 cm deep decreased in Bur L and Bur S by 25.1% and 14.7%, respectively, compared with the Unburned. A significant difference of total C between Bur L and Bur S was found only at the depth of 0–5 cm. Total N at 0–15 cm deep

Table 3.3
Physicochemical properties of soil and ash in burned and unburned spots

Treatment	Depth (cm)	Bulk density (Mg m^{-3})	Total C (Mg ha^{-1})	Total N (Mg ha^{-1})	pH	Total P (kg ha^{-1})	Total Ca (kg ha^{-1})	Total Mg (kg ha^{-1})	Total K (kg ha^{-1})	Total Na (kg ha^{-1})
Bur S	ash	-	1.48 a	0.03 a	-	36 a	2,120 a	239 a	681 a	17 a
Bur L	ash	-	4.14 b	0.01 b	-	132 b	6,395 b	612 b	2,186 b	39 b
						Avairable P	Exchangeable base			
							Ca	Mg	K	Na
						(kg ha^{-1})	(kg ha^{-1})			
Unburned	0-15	1.26 a	18.35 a	1.27 a	6.8 a	107 a	1,381 a	254 a	305 a	29 a
Bur S	0-15	1.18 a	15.64 b	1.15 a	7.6 b	338 b	1,354 a	263 a	372 ab	30 a
Bur L	0-15	1.16 a	13.73 b	1.08 b	8.1 b	920 c	2,151 b	252 a	408 b	16 a
Bur S	0-5	1.15 a	6.73 a	0.49 a	8.0 a	230 a	687 a	109 a	167 a	10 a
Bur L	0-5	1.14 a	5.08 b	0.39 a	8.5 a	450 b	1,240 b	116 a	184 a	4 a
Bur S	5-10	1.17 a	5.13 a	0.37 a	7.0 a	71 a	378 a	80 a	103 a	12 a
Bur L	5-10	1.18 a	4.66 a	0.37 a	7.5 a	394 b	530 a	69 a	114 a	6 a
Bur S	10-15	1.23 a	3.78 a	0.29 a	7.3 a	38 a	289 a	73 a	102 a	9 a
Bur L	10-15	1.23 a	3.99 a	0.32 a	7.2 a	76 a	381 a	67 a	110 a	6 a

Values are mean (*n* = 3).
Value followed by different letters vertically indicates that the means are significantly different ($P < 0.05$) at each depth.

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decreased only in Bur L by 15.0%, and seemed to decrease in Bur S by 9% but not significantly. Compared with the value of soil pH in the Unburned, those in Bur L and Bur S rose, although no significant difference was found between Bur L and Bur S. Available P at the depth of 0–15 cm increased with an increase in fire intensity and was higher in Bur L than that in Bur S at the depths of 0–5 and 5–10 cm. Exchangeable Ca and K at the depth of 0–15 cm increased only in Bur L compared with Unburned. The C contents of ash were 10%, and the total C, total P and bases in ash were significantly higher in Bur L than those in Bur S because the mass of ash was 37.07 ± 1.13 Mg ha^{-1} in Bur L and 12.26 ± 0.84 Mg ha^{-1} in Bur S.

3.3.4. Carbon and N mineralization

Figure 3.3 shows the cumulative C mineralization at a depth of 0–15 cm. The amount of C mineralization for 56 days of incubation was 951 ± 46, 939 ± 30, 1277 ± 36 kg C ha^{-1}, in the Unburned, Bur S and Bur L, respectively. Carbon mineralization in Bur L was significantly larger than those in Unburned and Bur S through incubation ($P < 0.05$). Also, C mineralization in Bur S was larger than those in Unburned only until 28 days of incubation ($P < 0.05$). Those differences of C mineralization among the treatments (Fig. 3.3) were mostly attributable to the difference of the daily rate of C mineralization for the first 3 days (Table 3.4). The rate for the first 3 days significantly increased in Bur L at all the depths compared with Unburned, but only at the depth of 0–5 cm in Bur S (Table 3.4).

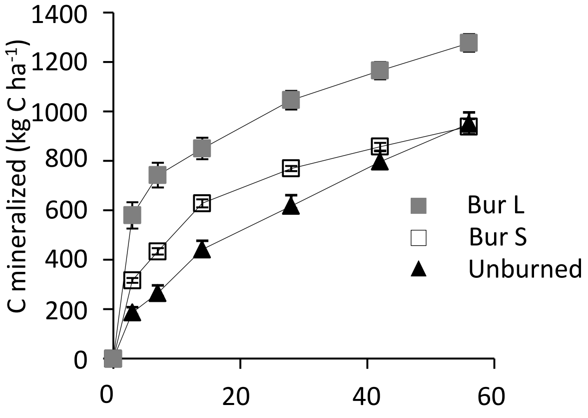


Fig. 3.3
Cumulative C mineralization at a depth of 0–15 cm during the incubation experiment. Bars indicate standard error (n = 3).

Table 3.4
Daily rate of C mineralization in burned and unburned spots

Treatment	Depth (cm)	Rate of Carbon mineralization (mg C kg^{-1} day^{-1})	
		0-56 days	0-3 day
Unburned	0-15	10 ± 0	31 ± 4
Bur S	0-5	20 ± 1 a *	130 ± 4 a *
Bur L	0-5	17 ± 0 a *	135 ± 3 a *
Bur S	5-10	8 ± 2 a	37 ± 13 b
Bur L	5-10	16 ± 2 b *	127 ± 17 a *
Bur S	10-15	4 ± 0 a	13 ± 1 b
Bur L	10-15	10 ± 1 b	72 ± 11 a *

Values are mean ± standard error (n = 3). Value followed by different letters vertically indicates that the means are significantly different ($P < 0.05$) between Bur L and Bur S at each depth. * represents significant difference compared with Unburned ($P < 0.05$).

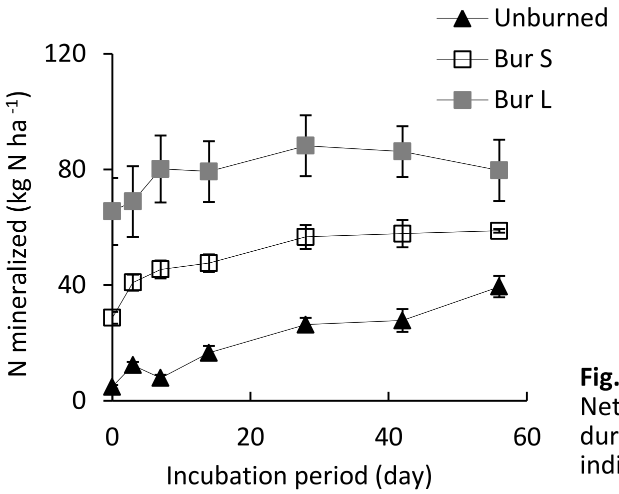


Fig. 3.4
Net N mineralization at a depth of 0–15 cm during the incubation experiment. Bars indicate standard error (*n* = 3).

Figure 3.4 shows N mineralization at the depth of 0–15 cm; burning increased the amount of inorganic N during the incubation ($P < 0.05$). Inorganic N was higher in Bur L than that in Bur S until 42 days of incubation ($P < 0.05$). Net N mineralization during the incubation (difference between inorganic N at 0 and 56 days), in Unburned, Bur S and Bur L showed no significant difference at 34.1 ± 3.7, 30.6 ± 2.7 and 14.1 ± 7.1 kg N ha^{-1}, respectively. Table 3.5 presents inorganic–N at 0 day incubation (In–N$_0$) and the daily rate of change in the amount of inorganic N. While In–N$_0$ increased by soil heating to the same extent between Bur L and Bur S at the depth of 0–5 cm, In–N$_0$ was higher in Bur L than that in Bur S at the depth of 5–10 and 10–15 cm. In–N$_0$ was present only as NH$_4$–N. Positive and negative values of the rate indicated net N mineralization and immobilization, respectively. The rate of N mineralization during the incubation was negative only in Bur L at the depth of 0–5 cm, although it was not significantly different among the treatments. At 0–3 days of incubation, N was immobilized significantly only in Bur L at the depth of 0–5 cm.

Table 3.5
Inorganic N at 0 day incubation and daily rate of N mineralization and immobilization at burned and unburned spots.

Treatment	Depth (cm)	In-N$_0$† (mg N kg^{-1})		Rate of Nitrogen mineralization or immobilization (mg N kg $^{-1}$ day^{-1})‡			
				0-56 days		0-3 day	
Unburned	0-15cm	2.5 ± 0.1		0.3 ± 0.0		1.3 ± 0.1	
Bur S	0-5cm	31.3 ± 3.6	a *	0.5 ± 0.2	a	1.9 ± 1.2	a
Bur L	0-5cm	43.1 ± 2.9	a *	-0.2 ± 0.2	a	-2.5 ± 0.8	b *
Bur S	5-10cm	11.7 ± 5.2	b *	0.2 ± 0.1	a	3.1 ± 0.2	a
Bur L	5-10cm	44.7 ± 11.1	a *	0.3 ± 0.1	a	2.2 ± 0.6	a
Bur S	10-15cm	7.8 ± 5.0	b	0.1 ± 0.1	a	2.0 ± 0.2	a
Bur L	10-15cm	25.5 ± 8.0	a *	0.3 ± 0.0	a	2.1 ± 0.5	a

Values are mean ± standard error (*n* = 3). Values followed by different letters vertically indicates that the means are significantly different between Bur L and Bur S at each depth ($P < 0.05$). * represents significant difference compared with Unburned ($P < 0.05$). † In-N$_0$ indicates inorganic N at 0 day of incubation. ‡ Positive value indicates N mineralization and negative value indicates N immobilization.

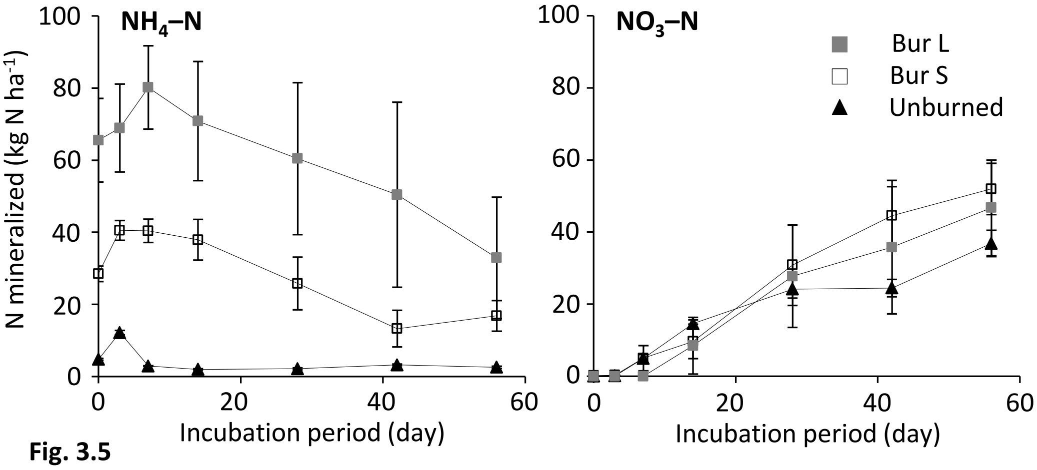


Fig. 3.5
The amount of NH$_4$–N and NO$_3$–N at a depth of 0–15 cm during the incubation experiment. Bars indicate standard error (*n* = 3).

Figure 3.5 indicates the amount of NH$_4$–N and NO$_3$–N at the depth of 0–15 cm. Nitrate–N was the predominant form of mineralization in Unburned, while NH$_4$–N was predominant in Bur S and Bur L at the beginning of mineralization. Nitrate–N increased in Bur S gradually after 14 days of incubation, while NH$_4$–N was present. Nitrate–N was not present in Bur L until 7 days of incubation. After 14 days of incubation, standard error of NO$_3$–N and NH$_4$–N in Bur L became very large because one of the three replicated samples in Bur L started nitrification after 14 days of incubation, while the other two samples in Bur L started after 28 days.

3.3.5. Maize production and weed growth

Table 3.6 shows the aboveground biomass of maize and weeds. The increased precipitation in 2009/2010 (986 mm) compared with 2008/2009 (762 mm) resulted in significantly higher production of maize grain and stover, especially for stover in the Unburned. Grain yield and mass of stover increased by burning in both years and grain yield was higher in Bur L than that in Bur S, while the area of Bur L and Bur S was not different, 6.9 and 7.5% of total cleared field, respectively (Table 3.1). Based on these results, the grain yield in Bur L and Bur S accounted for 21.5% and 15.7% of total yield, respectively. No woody weeds were present in Bur L in both years. The amount of woody weed biomass in Bur S was not significantly different from that in Unburned. The biomass of herbaceous weeds decreased by burning significantly in both years, and was not significantly different between Bur L and Bur S.

Table 3.6
Aboveground biomass of weed and maize in burned and unburned spots

	Maize stover (Mg ha^{-1})	Maize grain (Mg ha^{-1})	Herbaceous weed (Mg ha^{-1})	Woody weed (Mg ha^{-1})
2008/2009				
Unburned	1.06 ± 0.10 a	0.65 ± 0.09 a	0.94 ± 0.01 a	0.93 ± 0.01 a
Bur S	4.75 ± 0.42 b	2.27 ± 0.26 b	0.19 ± 0.01 b	0.34 ± 0.02 a
Bur L	6.58 ± 0.47 b	3.17 ± 0.34 c	0.02 ± 0.00 b	0.00 ± 0.00 b
2009/2010				
Unburned	3.37 ± 0.23 a	1.18 ± 0.19 a	0.26 ± 0.04 a	0.39 ± 0.17 a
Bur S	7.71 ± 0.63 b	2.51 ± 0.43 b	0.16 ± 0.05 b	0.18 ± 0.04 a
Bur L	8.25 ± 0.72 b	3.85 ± 0.38 c	0.10 ± 0.05 b	0.00 ± 0.00 b

Values are mean ±standard error (*n* = 3). Value followed by different letters vertically indicates that the means are significantly different (*P* < 0.05) in each year.

3.4. Discussion

Fire intensity increased with an increase in burned biomass per unit of burned area (Tables 3.1 and 3.2, Fig. 3.2). Soil was heated more deeply and for longer periods at higher temperatures in Bur L than in Bur S (Table 3.2, Fig. 3.2). Kendawang et al. (2004, 2005) also found that the maximum soil temperature increased with an increase in burned biomass. The maximum temperature with the same burned biomass in the above study in Southeast Asia, however, was lower than in this study, 100–150°C burning with 200 Mg ha^{-1} and 40–50°C burning with 100 Mg ha^{-1} at the depth of 5 cm. High soil moisture content in Southeast Asia (around 20%) may cause the lower maximum soil temperature observed there (Giardina et al., 2000a; Tanaka et al., 2001).

The increase in fire intensity led to a further decrease in total C and N at a depth of 0–5 cm (Table 3.3). Johnson et al. (2011) also showed a decrease in total C by 26% and 50% as well as a decrease in total N by 20% and 38% with low and high fire intensity, respectively, in a semiarid America. Some of the loss of C caused by soil heating will be compensated in second cropping year because ash will be incorporated with soil by plowing (Table 3.3).

Carbon mineralization during the first 3 days of incubation and NH_4–N (In–N_0) at a depth of 0–15 cm increased with an increase in fire intensity (Fig. 3.3, Table 3.4). Those increases might be derived from the mortality of microbes; microbe mortality started when temperatures reached 80–120°C (DeBano et al., 1998). Therefore, C mineralization and NH_4–N (In–N_0) was higher in Bur L than in Bur S because microbes were killed in deeper soil in Bur L than that in Bur S because of the deeper heating in Bur L (Table 3.2, Fig. 3.2).

An increase in C mineralization caused by soil heating during the early stage of incubation was also observed in Southeast Asia (Kendawang et al., 2004). Despite the documented increase in C mineralization with an increase in fire intensity, C mineralization at the end of incubation was higher only in Bur L compared with that in the Unburned (Fig. 3.3). Presumably, soil heating in Bur S might produce not only mineralizable organic material through volatilization of SOM or mortality of microbial biomass but also recalcitrant forms of C such as char or black C by imperfect combustion of SOM (González-Pérez et al., 2004).

An increased release of NH_4–N caused by soil heating based on an increase in fire intensity was also found in a semiarid America (Johnson et al., 2011) and Southeast Asia (Tanaka et al., 2001, 2004). Although the amount of inorganic N was highest in Bur L during the incubation at a depth of 0–15 cm, net N mineralization was apparently the lowest in Bur L among the three treatments (Fig. 3.4). Although the rate of C mineralization and In–N_0 were the same between samples at a depth of 0–5 cm and 5–10 cm in Bur L (Tables 3.4 and 3.5), N was significantly immobilized at a depth of 0–5 cm in Bur L during the first 3 days of incubation (Table 3.5). This might be related to the decrease in the N content of labile organic matter at a depth of 0–5cm, which was suggested by the significant decrease in total N only at a depth of 0–5cm.

Recovery of nitrification activity at the depth of 0–15 cm was delayed with an increase in fire intensity (Fig. 3.5) which reflected nitrifier mortality starting at 90°C (Nearya et al., 1999; Dunn et al., 1979). The time needed for nitrification activity to recover in Bur L varied among the samples (Fig. 3.5). The recovery of nitrification activity might be sensitive for even a little difference of fire intensity which occurred among the spots burned with different emergent trees. The increase in soil pH (to 8.1) by burning may not influence nitrifying bacteria because the pH was already neutral before burning (Table 3.3). Ste-Marie and Paré (1999) found that the pH at which nitrifying bacteria were inhibited was less than 5 or more than 10.

The amount of available P increased with fire intensity (Table 3.3). Heat induced microbial mortality may have been the primary factor leading to the increase in available P (Giardina et al., 2000a). In Bur L, available P and exchangeable Ca and K increased because degradation of SOM was promoted by the high maximum temperature and long duration of burning (Giardina et al., 2000a). The exchangeable bases and available P also seemed to increase depending on fire intensity in Southeast Asia (Tanaka et al., 2004). Total P and bases in ash will gradually be incorporated into the soil through the percolation of rain and by plowing during the second cropping year.

Herbaceous weeds had a low resistance to soil heating (Table 3.6); weed seeds were killed at about 90°C resulting in low herbaceous biomass (Martin et al., 1975). In addition, biomass of woody weeds decreased with strong fire intensity (Table 3.6) because their large roots could survive only low intensity fires.

In Unburned spots, accounting for 85% of the total field, maize yield was 0.7 Mg ha^{-1} because of the low available nutrient (Tables 3.1 and 3.6). In Bur S and Bur L, covering 7.5% and 6.9% of the total field, maize yield was 2.3 Mg ha^{-1} and 3.2 Mg ha^{-1}, respectively (Table 3.6). Those increases in maize yield are due to the increase in available nutrient by the degradation of SOM and leachate from ash, and the decrease in weeds. Those extents were more pronounced in Bur L than in Bur S. However, the content of C and N in SOM decreased more in Bur L than in Bur S (Table 3.3). Thus, the recent slash-and-burn practice, with the presence of both emergent and bush tree piles, increased the spatial variability in SOM, available nutrients and weeds, which affected maize grain.

3.5. Conclusion

In Eastern Province, Zambia, the effects of soil heating on changes of SOM followed by nutrient release depended on fire intensity. The amounts of burned tree biomass, 80 Mg ha^{-1} (bush trees), and 200 Mg ha^{-1} (emergent trees), had different impacts on the soil nutrients, which was controlled by the maximum temperature and duration of soil heating. As fire intensity increased, increases in C mineralization, NH_4–N, exchangeable Ca and K, and available P were observed through the increased degradation of SOM and mortality of microbes. Net N mineralization did not increase through burning partly because the N content of labile organic matter decreased by burning. Even though the burned spots with bush tree and emergent tree piles covered only 7.5% and 6.9% of total cleared field, grain yield increased to 15% and 21% of the total grain yield for the entire field, respectively. However, a more pronounced decrease in total C and N was observed in spots burned with emergent trees than those with bush trees. Therefore, because more areas are being burned with bush trees owing to the decrease in emergent trees, grain yield may decrease, although the severe decrease in SOM may be alleviated. This study clarified that the recent changes in slash-and-burn practice brought high spatial variability of SOM and crop production inside the cleared field with three extents of fire intensity. In following Chapter 4 and 5, the effects of cropping and short-fallow rotation on SOM and crop production will be elucidated at spots unburned and burned with emergent and bush tree piles.

Chapter 4

Effects of cropping and short-natural fallow rotation on soil organic matter

4.1. Introduction

Many tropical soils are poor in nutrients and rely on the recycling of nutrients from soil organic matter (SOM) to maintain crop productivity (Solomon et al., 2000). Natural fallow is still a useful management for the restoration of SOM, especially for smallholders in the area (Nhantumbo et al., 2009). This is attributed to an increase in litter returned to the soil during fallow periods (Funakawa et al., 2006; Adiku et al., 2008), a decrease in SOM decomposition when plant litter is left on the soil surface and the formation of soil aggregates (Balesdent et al., 1998; Huggins et al., 1998; Ouattara et al., 2006). In semiarid regions of southern Africa, conversion of miombo woodland to cropland has increased recently (Walker and Desanker, 2004; Mapanda et al., 2013). This increase has shortened the fallow length from >20 years to <5 years (Chirwa et al., 2004) and investigation into whether the decrease in SOM during cropping after slash-and-burn could be restored during the shortened fallow period is necessary.

SOM decreased by cropping has been well explained. Carbon contents of SOM (SOC) decreased by the decrease in input of crop residue and weeds, increase in decomposition of the input by incorporation and in decomposition of SOM by breakdown of soil aggregation due to plowing (Balesdent et al., 1998; Huggins et al., 1998; Six et al., 1998; Murty et al., 2002; Promsakha et al., 2005). On the other hand, N contents of SOM (SN) decreased by no newly input such as fertilizer and increase in output such as grain yield and leachate induced by increase in SOM decomposition due to plowing (Zingore et al., 2005). In semiarid tropics of Africa, SOC and SN decreased 2.0 Mg C ha^{-1} year^{-1} and 0.2 Mg N ha^{-1} year^{-1}, respectively, during 3-year cropping after clearing woodland (Zingore et al., 2005).

Furthermore, weed composition in southern Africa may change with longer cropping periods or increase in fire intensity in response to the decrease in coppicing ability of roots or stumps (Walker and Desanker, 2004). This could lead to the different decomposition rates of the input (Mafongoya and Nair, 1997). However, few studies have attempted to reveal the effect of weed composition on SOM.

The changes in amount and composition of input may affect the labile SOM fraction such as coarse organic matter (COM >2000 μm) and particulate organic matter (POM 2000–53 μm) more rapidly than SOC (Cambardella and Elliott, 1992; Balesdent et al., 1998; Solomon et al., 2000, 2002). Mapfumo et al. (2007) showed that POM was increased by incorporation of large amounts of crop residue and changed in response to the different quality of plant materials, although SOM did not change clearly in dry tropical cropland in Zimbabwe.

In turn, the recovery of SOM including COM and POM during short fallow periods could be changed by differences in the extent of SOM decrease and coppicing ability affected by cropping period and fire intensity (Aweto, 1981; Mobbs and Cannell, 1995; Styger et al., 2007, 2009). However, it is difficult to obtain reliable information on field history and the uniform place of initial SOM (Birch-Thomsen et al., 2007; Woollen et al., 2012), which affected recovery of the SOM and vegetation during fallow.

Thus, the changes of SOM including COM and POM during cropping and short fallow rotation under the slash-and-burn agriculture had not been comprehensively related to the composition and amount of input, especially in short fallow with different short cropping periods. Therefore, the objective of this chapter was to evaluate the changes of SOM, COM and POM under different cropping period followed by short fallow under the slash-and-burn agriculture, with reference to the changes in composition and amount of input.

4.2. Materials and methods

4.2.1. Experimental design

Plots of cropping and short-fallow rotation consisting of spots unburned (Unburned), and spots burned with emergent tree (Bur L) and with bush trees (Bur S) were established as described in Chapter 2. For this chapter, used were the three treatments of short cropping plots and the three treatments of fallow plots in 2009/2010, the four treatments of short cropping plots and the six treatments of fallow plots in 2010/2011 and in 2011/2012 (Fig. 4.1). The only unburned plots for 10- and 40-year cropping were divided into cropping and fallow treatments in October 2010. Plots for long fallow were also established close to short and long cropping plots.

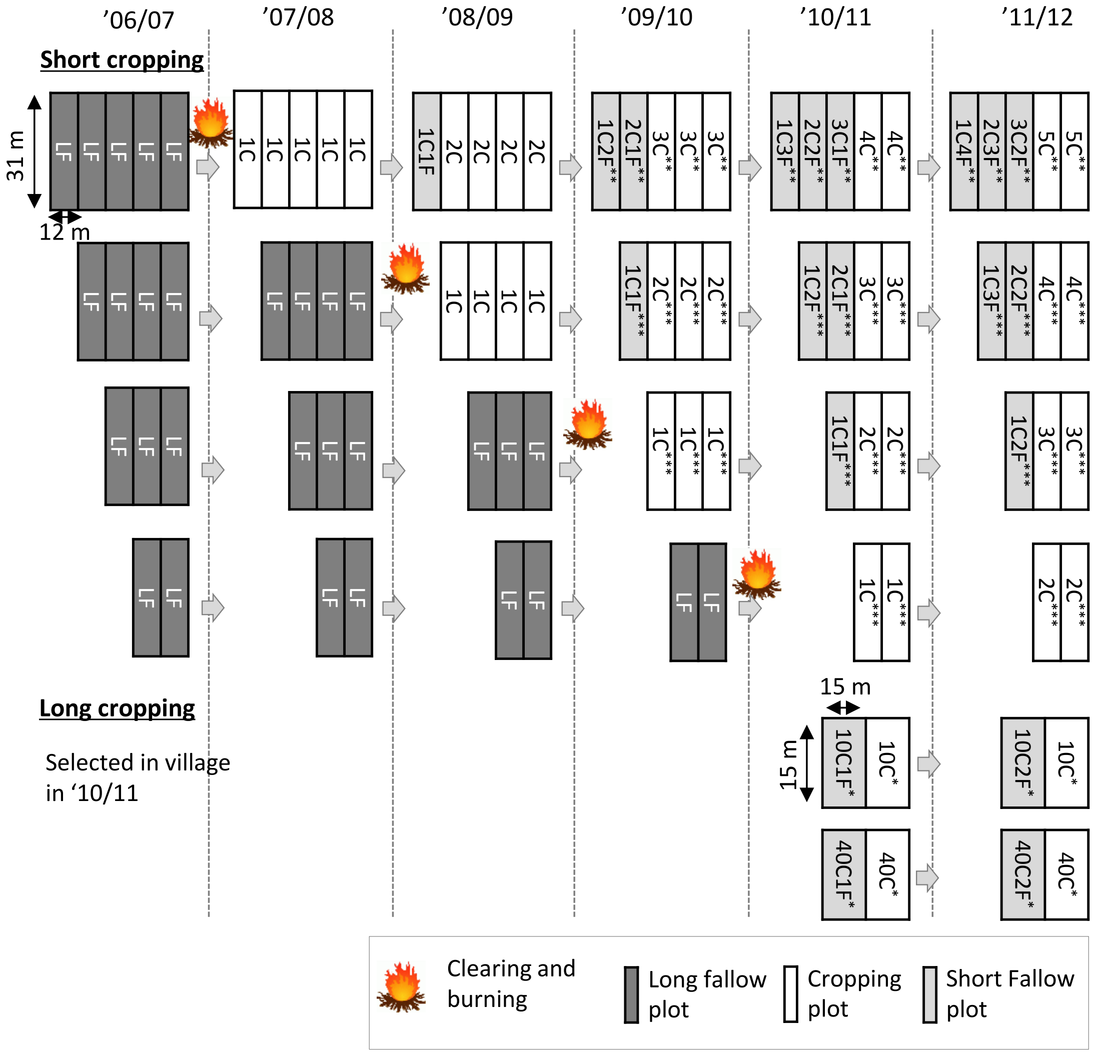


Fig. 4.1
Description and history of the experimental treatments with sampling location.
Values followed by C or F shows the period of cropping or fallow, respectively. LF represents long fallow, C represented cropping and F represents fallow. Samples of soil and plant were collected at only Unburned (*), at Unburned and Bur L (**), and at Unburned, Bur L and Bur S (***). In short fallow in Bur L and Bur S, only soil samples were collected (did not collect plant samples). Unburned indicates spots unburned, Bur L indicates spots burned with emergent trees and Bur S indicates spots burned with bush trees.

4.2.2. Environmental factors

Soil temperature at a depth of 5 cm was monitored in every 20 minutes in cropland (Unburned and Bur L) and long fallow (CS215 thermistor probes connected to a CR1000 data logger; Campbell Scientific, Inc., USA), and in cropland (Unburned and Bur L) and 4-year fallow in Unburned (Ondotori Jr. TR51A, T&D Corporation, Japan). Soil volumetric water content at the depth of 0–10 cm was recorded in every 20 minutes in cropland (Unburned and Bur L), and 4-year and long fallow (Easy AG probe, Sentek pty Ltd., Australia, connected to a CR1000 data logger). Permanent wilting point (–1.5 MPa) and field capacity (–15 kPa) at 0–15 cm were determined in intact core samples by the centrifugation method and soil column method, respectively (Klute, 1986).

4.2.3. Soil sampling and analysis

Soil samples at 0–15 cm were collected by a 0.3 L core in April 2010, 2011 and 2012 (Fig. 4.1). The soil samples of the adjacent LFs of short cropping, 10C and 40C were also collected in April 2011 (Fig. 4.1). The samples collected at three locations in a plot were mixed thoroughly to make a composite sample. The composite samples were sieved to 2 mm after removing visible plant detritus. The organic material >2 mm including visible plant detritus was separated from gravels, washed by water and ground by ball mill (PM 200; Retsch GmbH, Germany) and referred to as coarse organic matter (COM). Particulate organic matter (POM) was separated from soil by size fraction (2000–53 μm). A 20 g of soil was dispersed in 60 mL of 5 g L^{-1} sodium hexametaphosphate for 15 hours in a reciprocating shaker and rinsed with deionized water through a 53 μm sieve (Cambardella and Elliott, 1992). What remained on the sieve was weighed after drying at 60°C for 24 h and ground to fine powder (Spargo et al., 2011). The contents of total C and N in the soil (SOC, SN), COM (COM-C, COM-N) and POM (POM-C, POM-N) were analyzed by dry combustion method with a NC analyzer (Vario Max CHN; Elementar, Germany). The C and N contents of mineral-associated organic matter (MOM-C, MOM-N) were calculated by subtracting POM from SOM (Bayer et al., 2001).

4.2.4. Plant sampling and analysis

Maize stovers and grains in each cropping plot were collected from three hills in April 2010, 2011 and 2012 at harvesting time (Fig. 4.1). At weeding and harvesting time, woody and herbaceous weeds in each cropping plot were collected separately from three quadrates of 1 × 1 m. At weeding and harvesting time, woody and herbaceous weeds in each cropping plot were collected separately from three 1 × 1 m quadrats. Herbaceous litter in each fallow plot was collected from three 1 × 1 m quadrats in April 2010, 2011 and 2012. Woody litter was collected monthly by a round litter trap with a diameter of 76 cm with five replicates. Root samples at 0–15 cm were collected by a 0.3 L of core with a diameter of 3.2 cm at the same places where the maize and weed samples were collected in May 2012. In addition, root samples were collected from another three places in each plot and were sieved and rinsed on 0.5 mm mesh to collect fine roots (diameter <2 mm). All these samples were weighed after drying at 70°C for 48 h. The root biomass in 1C and 1F was calculated from the linear relationship between aboveground biomass and root biomass (r^2 = 0.3) because the treatments were not present in 2011/2012 (Fig. 4.1). All the samples of plant materials were ground to fine powder and the C and N contents of those samples were analyzed.

Basal diameter (BD) of all trees higher than 1.5 m in the fallow plots was measured in April 2011 and May 2012. Then, 46 trees of the most common six species in the plots were destructively harvested for the calculation of dry weight in 2012. The samples were weighed *in situ* and some of them were weighed after oven drying for a week. The dry weight and BD of the trees were fitted to the following allometric equation (Ryan et al., 2010; Chidumayo, 2013):

$$ln\,(\mathrm{B}) = a \times ln(\mathrm{BD}) - b \qquad (4.1)$$

where B is dry weight of tree (g) and BD is basal diameter (mm), and *a* and *b* are constant.

4.2.5. Measurement of *in situ* decomposition of plant materials

The decomposition of the plant materials under field conditions was estimated by the litter bag method in long fallow, cropland (Unburned and Bur L) and short fallow after cropping plots. Nylon bags (18 × 15 cm) of 2 mm mesh were filled with 10 g of maize stover cut into 5 cm lengths, woody litter including branches and leaves, or herbaceous weeds cut into 5 cm lengths. The litter bags were placed on the soil surface in the fallow and at 5 cm depth in cropland plots because the plant was incorporated by plowing in cropland. All kinds of litter bags were placed in LF, 1C, 4C, 1F and 3F in November 2010 with 5 replicates. They were collected in April 2011, and dried at 70°C for 48 h after removing soil with water, and weighed. The C and N contents were analyzed after ground to fine powder.

4.2.6. Statistical analysis

All statistical analyses were performed with Sigma plot 11.0 (SYSTAT Software Inc., CA, USA). All data were expressed on a dry-weight basis (mean ± standard error). For data in cropland, a one-way analysis of variance (ANOVA) was used to detect the significant differences of variables. Differences between treatments in fallow were tested by a two-way ANOVA (cropping period before fallow × fallow period). When the ANOVA indicated a significant difference, mean comparisons were performed with Tukey's Kramer multiple comparison test.

4.3. Results

4.3.1. Environment factors

Mean soil volumetric water content (SVW) and mean daily soil temperature in 2011/2012 is shown in Fig. 4.2. Fluctuation of the soil temperature and SVW in 2009/2010 and 2010/2011 was almost same as those in 2011/2012 (data shown in Chapter 5, Fig. 5.4). Those fluctuations in 2- and 4-year fallow were also same (data for 2-year fallow not shown). The soil temperature in the rainy season from the first rain to the beginning of May was higher in Unburned (26.0°C) and Bur L (26.5°C) than in long fallow (23.9°C) and in 4-year fallow (24.6°C). Fluctuation of SVW was not different among the treatments through the year. In the dry season, SVW was always below the permanent wilting point of –1.5 MPa (11.8%).

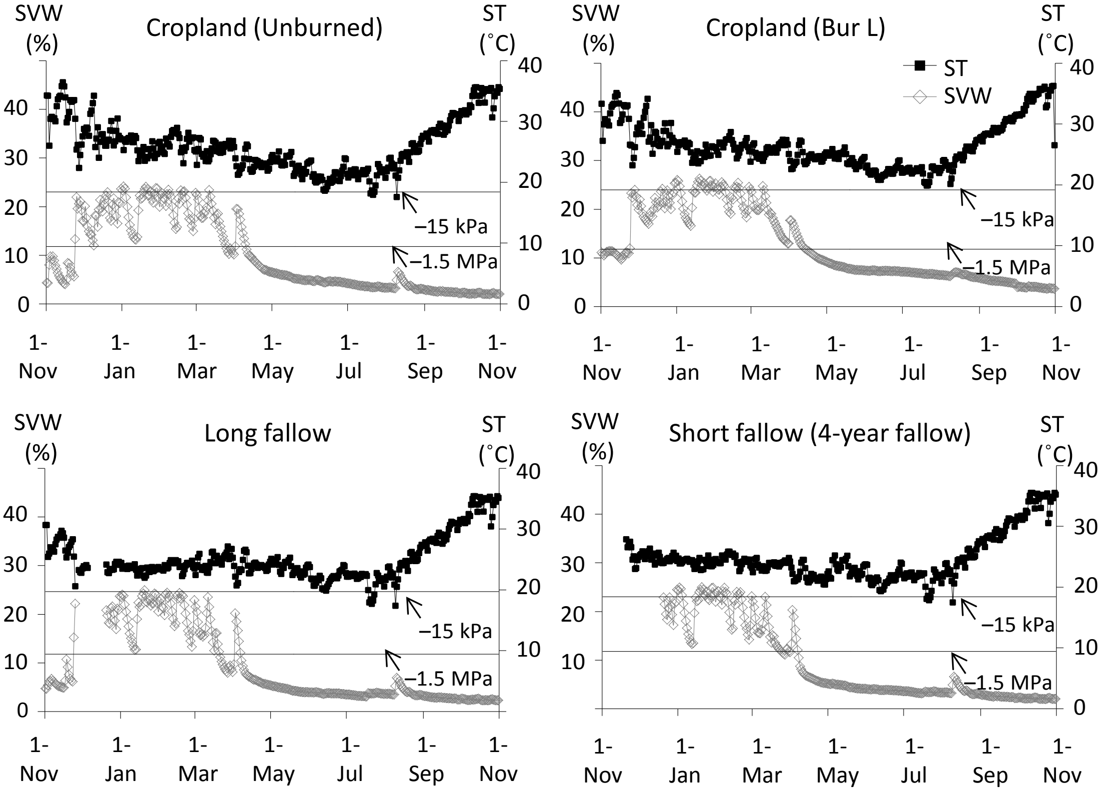


Fig. 4.2
Fluctuation of mean daily soil volumetric water content (SVW) and mean daily soil temperature (ST) in 2011/2012.

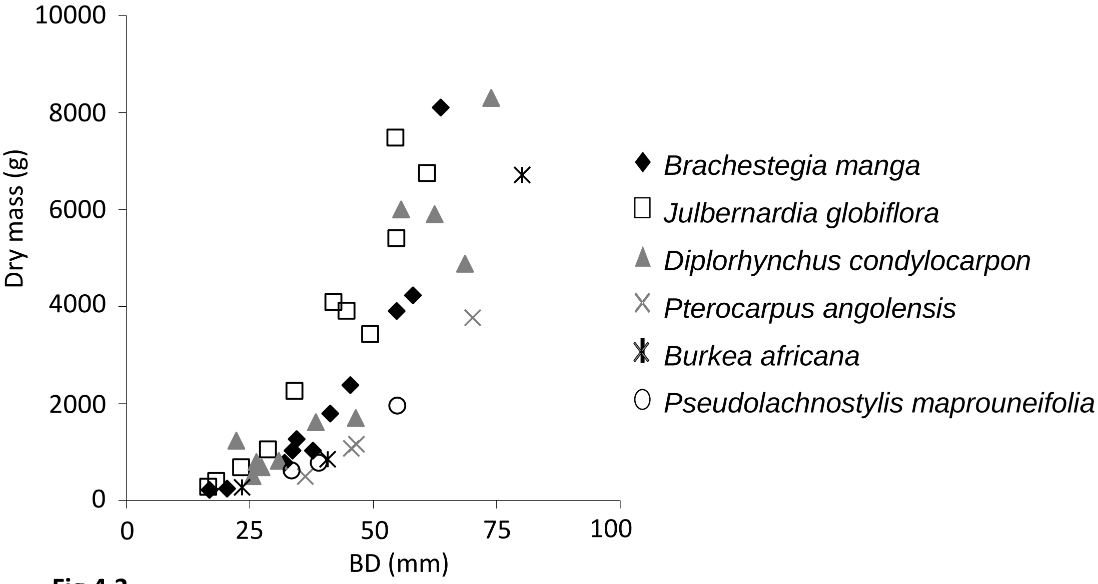


Fig.4.3
Relationship between dry mass of tree and basal diameter (BD) in miombo woodland.

Table 4.1
Decomposition ratio of woody, herbaceous and maize plant under field conditions

	Decomposition ratio (%)		
	Maize (C/N = 84.9)	Herbaceous weed or litter (C/N = 61.2)	Woody weed or litter (C/N = 46.0)
Mass			
[¶]LF	91.9 ± 1.8 a	46.9 ± 5.1 a	49.7 ± 12.0 a
SF	83.3 ± 2.6 a	54.7 ± 3.7 a	41.9 ± 3.9 a
Unburned	87.1 ± 3.4 a	80.7 ± 3.9 b	64.2 ± 15.4 a
Bur L	90.9 ± 6.5 a	92.8 ± 1.1 b	-
TC			
LF	94.9 ± 1.4 a	50.5 ± 2.3 a	48.2 ± 11.5 a
SF	88.4 ± 1.7 a	62.2 ± 5.2 a	43.0 ± 7.6 a
Unburned	91.5 ± 2.7 a	86.5 ± 4.3 b	71.7 ± 14.8 a
Bur L	93.6 ± 4.6 a	94.9 ± 0.75 b	-
TN			
LF	93.6 ± 1.4 a	81.9 ± 2.3 a	55.1 ± 11.5 a
SF	90.1 ± 1.7 a	72.7 ± 5.2 a	55.5 ± 7.6 a
Unburned	91.4 ± 2.7 a	83.6 ± 4.3 a	65.8 ± 16.9 a
Bur L	87.7 ± 8.8 a	90.3 ± 1.42 a	-

[¶] LF represents long fallow, Unburned and Bur L represent Unburned and Bur L during cropping, and SF represents short fallow of Unburned. Values are mean ±standard error (*n*=5). Value followed by vertical different letter (a and b) indicates that the mean was different significantly among treatments of each plant materials.

4.3.2. Allometric equation

The relationship between aboveground biomass (B) of trees and BD is shown in Fig. 4.3 and was significantly correlated with BD among all of the six species ($r^2 = 0.93$).

$$\ln(B) = 2.38 \times \ln(BD) - 1.88 \quad (4.2)$$

BD range of application was from 16.6 to 80.5 mm.

4.3.3. Decomposition ratio of the plant materials

Table 4.1 shows decomposition of the plant materials. Almost all maize stover was decomposed in all the treatments in a rainy season. Almost all herbaceous weed or litter was decomposed in cropland (Unburned) in a rainy season, while only half of that was decomposed in long and short fallow. Half of woody weed or litter was decomposed in all the treatments in a rainy season.

4.3.4. Maize grain yield

Table 4.2 shows maize grain yield in Unburned, Bur L and Bur S. In Unburned, the grain yield decreased significantly only after cropping for 40 years. On the other hand, the higher grain yield lasted for 2 years in Bur L, for 1 year in Bur S compared to that in Unburned. After that, the grain yield became same among Unburned, Bur L and Bur S.

Table 4.2
Maize grain yield in Unburned, Bur S and Bur L for the three cropping season

Cropping period	Unburned Mg ha^{-1}		Bur S Mg ha^{-1}		Bur L Mg ha^{-1}	
1C	0.7 ± 0.1	aA	2.6 ± 0.2	aB	3.3 ± 0.2	aC
2C	0.6 ± 0.1	aA	0.8 ± 0.1	bA	2.1 ± 0.2	bB
3C	0.8 ± 0.1	aA	1.0 ± 0.2	bA	1.3 ± 0.2	cA
4C	0.9 ± 0.1	aA	1.0 ± 0.2	bA	1.2 ± 0.3	cA
5C	0.8 ± 0.2	aA	–		1.6 ± 0.4	cA
10C	0.8 ± 0.1	a	–		–	
40C	0.5 ± 0.1	b	–		–	

Values are mean±standard error (*n*=6 for 1C, 4C, 10C, *n*=9 for 2C and 3C, *n*=3 for 5C, 40C for *n*=2). Values followed by vertically different letters (a and b) indicates that the mean was different significantly among cropping periods. Values followed by horizontally different letters (A, B and C) indicate that mean was different significantly among Unburned, Bur S and Bur L.

4.3.5. Soil organic matter in unburned spots

Carbon and N contents of COM (>2000 μm), POM (2000–53 μm) and MOM (<53 μm) in Unburned during cropping are shown in Fig. 4.4. Carbon and N contents of SOM (SOC, SN) did not decrease by cropping for 1 to 5 years. Decrease in SOC by 24% and 43% as well as SN by 26% and 36% after cropping for 10 and 40 years (10C and 40C), respectively, were observed compared to adjacent long fallow. Carbon and N of COM at the time of clearing decreased after 1-year cropping significantly. The C content of COM and POM tended to decrease gradually with increase in short cropping period, while the N contents did not change. More than half of C and N contents of COM and POM decreased significantly after 10-year cropping.

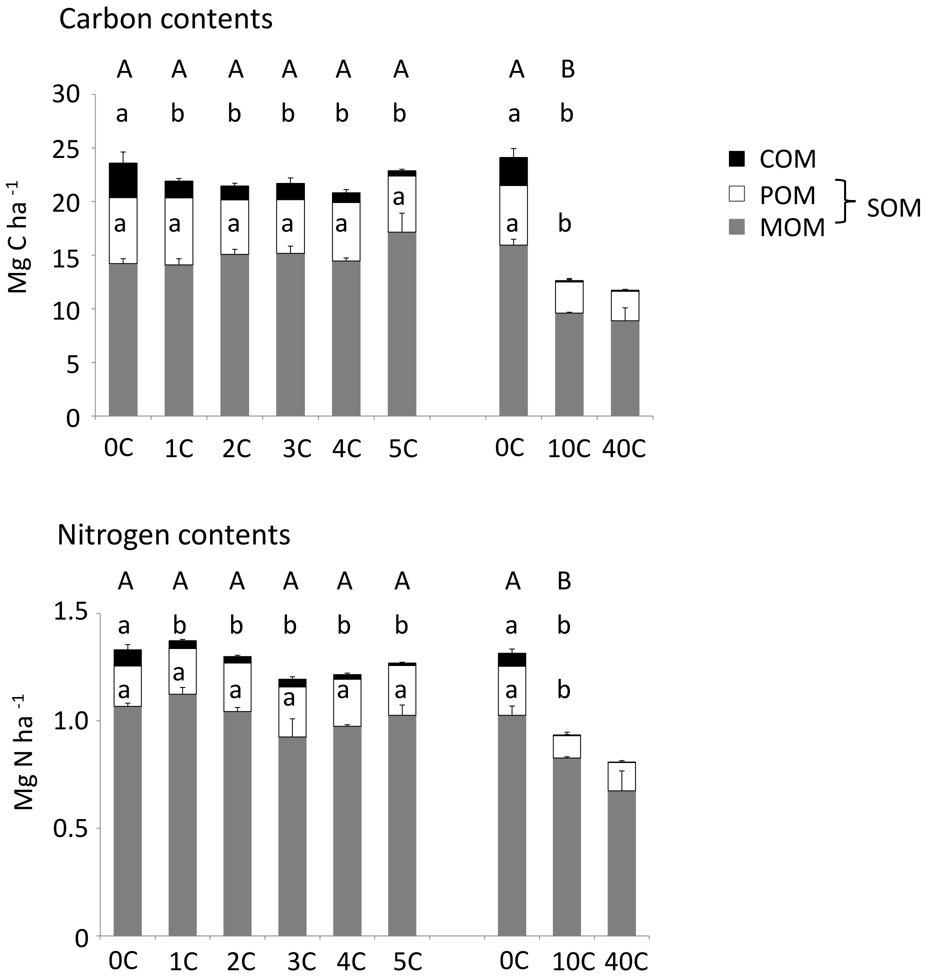


Fig. 4.4

Carbon and N contents of COM, POM and MOM during cropping in Unburned. Bars indicate the standard error (1C, 4C, 10C were *n*=6, 2C and 3C were *n*=9, 5C was *n*=3, 40C was *n*=2). Different uppercase letters (A and B) indicate that the means of SOM are significantly different ($P < 0.05$). Different lowercase (a and b) letters of upper and lower line indicate significant difference of the means of COM and POM, respectively ($P < 0.05$).

Figure 4.5 shows C and N contents of COM, POM and MOM during fallow after different cropping periods. The C and N contents of COM and MOM were not restored during fallow after any copping for 1 to 10 years. The C content of POM, however, was higher in fallow after 3-year cropping than in fallow after 1-, 2-, 10- and 40-year cropping. POM-C increased gradually during fallow after 10-year cropping ($P < 0.05$), and fallow after 40-year cropping.

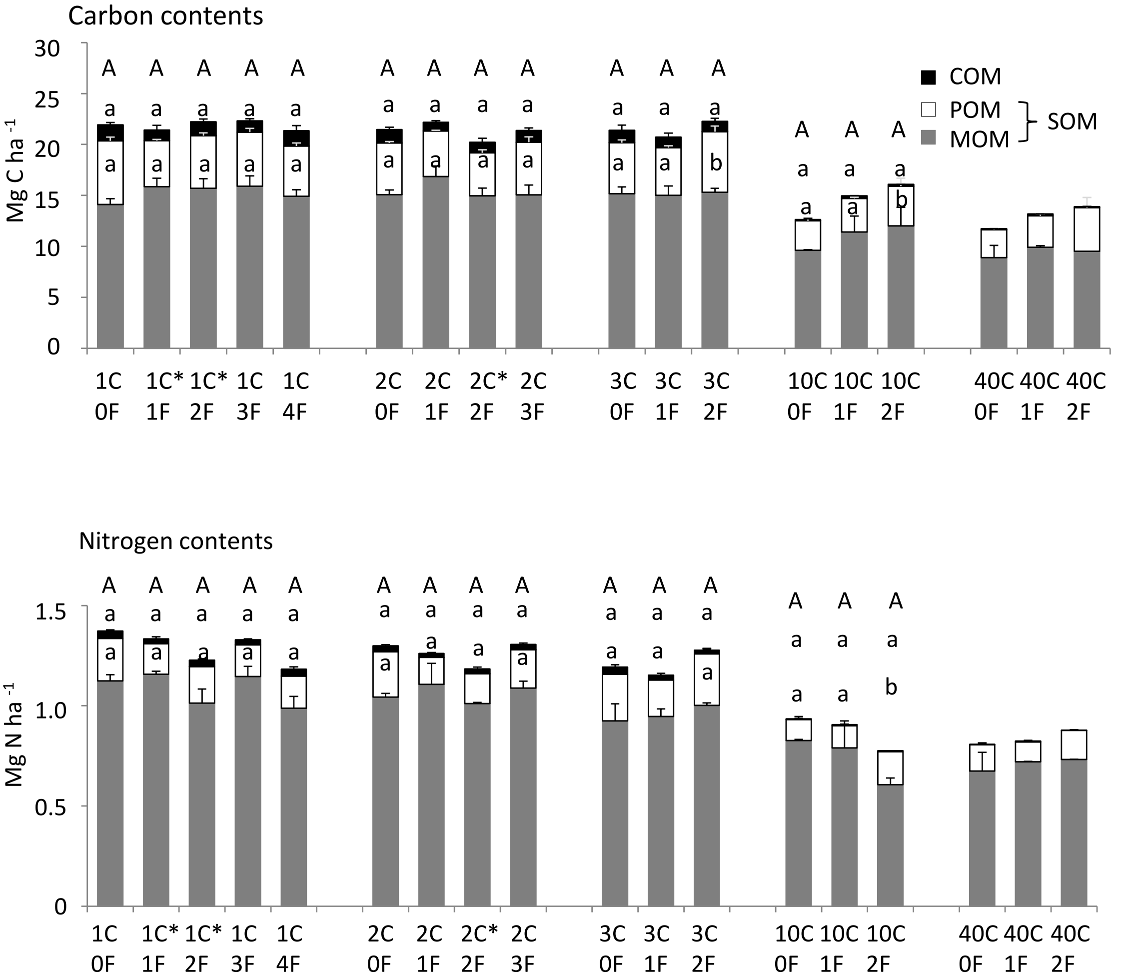
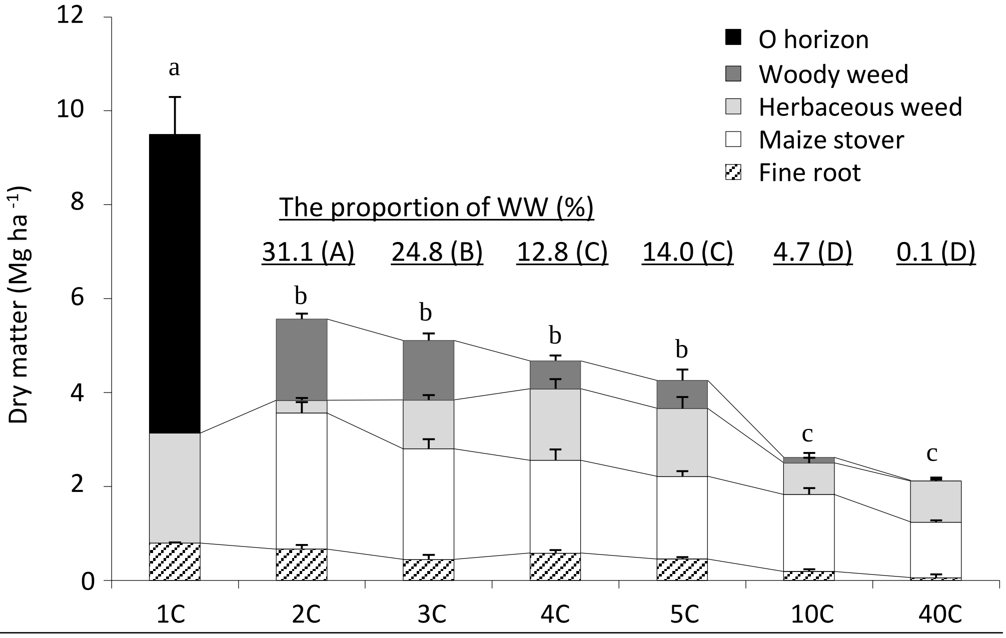


Fig. 4.5
Carbon and N contents of COM, POM and MOM during short fallow after different cropping periods in Unburned. Bars indicate the standard error (treatment with was *n*=6, 40C1F and 40C2F was *n*=2, and the others were *n*=3). Different uppercase letter (A) indicates that the means of SOM are significantly different ($P < 0.05$). Different lowercase letter (a and b) of upper and lower line indicates significant difference of the means of COM and POM, respectively ($P < 0.05$).

4.3.6. Vegetation and input of plant materials in unburned spots

The input of plant materials during cropping is shown in Fig. 4.6. The input returned to soil in 1-year cropping was 9.5 Mg ha^{-1}, mainly from the O horizon in the long fallow. Then the input decreased to 5.2 Mg ha^{-1} in 2-year cropping, and gradually decreased to 4.3 Mg ha^{-1} in 5-year cropping. After 10- and 40-year cropping, the total input fell to 2.3 Mg ha^{-1}. The C and N contents of the input also decreased gradually with increase in cropping period. Composition of the input changed with an increase in cropping period. The proportion of woody weeds to total input decreased as the cropping period increased.



	1C	2C	3C	4C	5C	10C	40C
Input of C (Mg C ha^{-1})	4.9	2.6	2.4	2.1	2.0	1.2	1.0
Input of N (kg N ha^{-1})	81.3	46.4	39.5	30.9	28.7	14.5	11.0

Fig. 4.6
The composition and amount of input of plant materials during cropping in Unburned. Bars indicate the standard error (1C, 4C, 10C were *n*=6, 2C and 3C were *n*=9, 5C was *n*=3, 40C was *n*=2). The ratio of WW shows the ratio of woody weed to total input, and different uppercase letter (A,B,C,D) indicates that the means of the proportion of woody weed are significantly different ($P < 0.05$). Different lowercase letter (a,b,c) indicates that the means of total input are significantly different ($P < 0.05$), significantly.

Vegetation type in the long fallow was almost the same between short cropping sites and long cropping sites, meaning the vegetation data could be compared. The recovery of woody biomass in fallow is shown in Fig. 4.7. The changes in woody biomass significantly depended on both the cropping and the fallow period. In fallow after 1- to 3-year cropping, woody biomass increased with an increase in fallow period (P<0.05). The woody biomass recovered during fallow, however, decreased with an increase in cropping period before the fallow. A notable difference was found in 2 year fallow after 1-, 2- and 3-year cropping, in the order of 4.41 (1C2F), 2.87 (2C2F), and 1.91 Mg ha^{-1} (3C2F), respectively. Very little woody biomass was recovered in fallow after 10- and 40-year cropping.

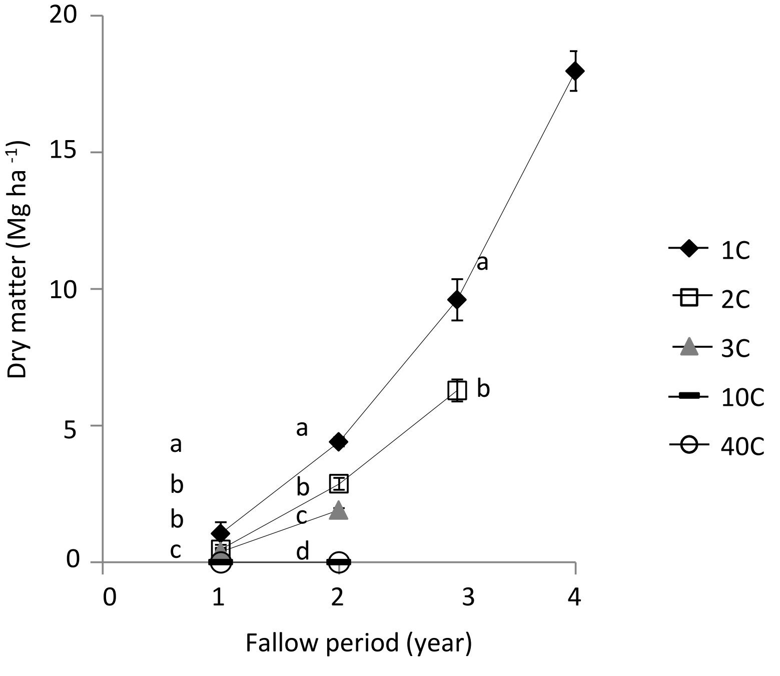
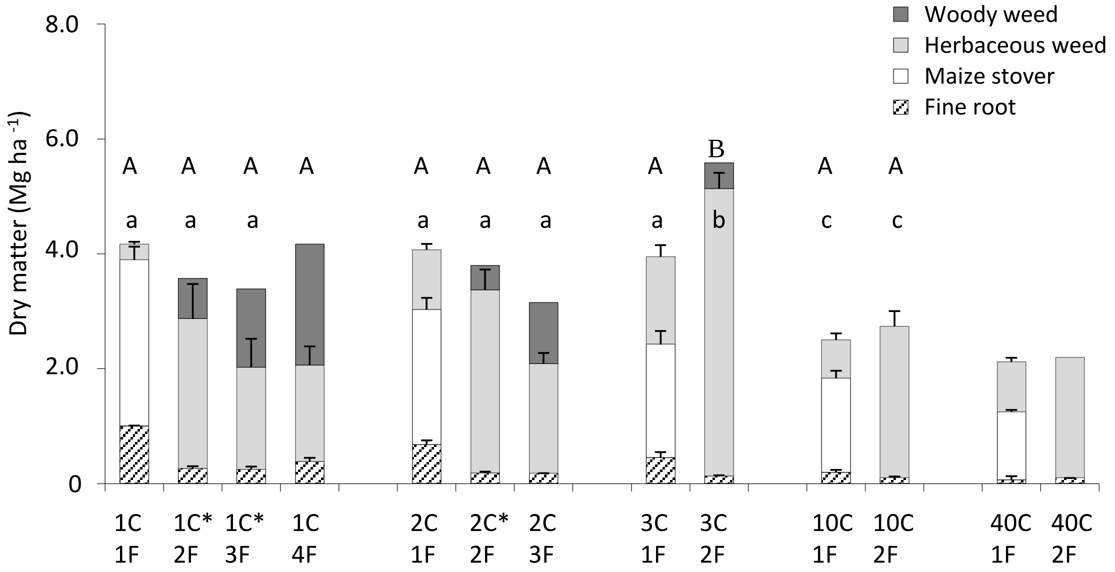


Fig. 4.7
Recovery of woody biomass during fallow after different crop periods in Unburned. Bars indicate the standard error (n=3, 40C was n=2). Different letters vertically indicate that the means are significantly different (P < 0.05).



	1C 1F	1C* 2F	1C* 3F	1C 4F	2C 1F	2C* 2F	2C 3F	3C 1F	3C 2F	10C 1F	10C 2F	40C 1F	40C 2F
Input of C (Mg C ha^{-1})	1.8	1.7	1.7	2.1	1.8	1.8	1.5	1.7	2.6	1.1	1.2	1.0	1.0
Input of N (kg N ha^{-1})	21.3	27.5	33.1	45.1	21.1	26.0	28.7	20.6	36.4	12.6	15.7	10.8	12.6

Fig. 4.8
The composition and amount of input of plant materials during fallow in Unburned.
Bars indicate the standard error (treatment with was n=6, 40C1F and 40C2F was n=2, and the others were n=3). Different uppercase letters (A and B) horizontally indicate that the means of total input are significantly different between the different fallowing periods after each cropping period in each depth ($P < 0.05$); different lowercase letters (a-c) horizontally indicated that the means of total input are significantly different between each fallowing period after different cropping periods ($P < 0.05$).

The input of plant materials in fallow is shown in Fig. 4.8. The input returned to soil became significantly lower in fallow after short cropping than in cropland (Figs. 4.6 and 4.8) (P<0.05). Only the input in 2-year fallow after 3-year cropping (3C2F) was higher than that in cropland. The amount of input had no difference among any fallow period after 1- or 2-year cropping. The amount of input in fallow after 10- and 40-year cropping was almost same as that in cropland. The input composed of maize and herbaceous weed in 1-year fallow. After that, the composition of input changed, reflecting the change of woody biomass (Fig. 4.7). While the amount of woody litter increased with increase in fallow period from 1C2F to 1C4F and from 2C2F to 2C3F, it decreased with increase in cropping period from 1C2F, 2C2F to 3C2F, and from 1C3F to 2C3F. The C and N contents of the input also decreased with increase in cropping period (Fig. 4.8). No woody litter was found in fallow after 10- and 40- year cropping. As a result, the woody litter proportion to total input decreased during fallow with increase in cropping period.

4.3.7. Soil organic matter in burned spots

Carbon and N contents of COM, POM and MOM during cropping are shown in Fig. 4.9. As C and N contents of SOM decreased by burning (Table 3.3), those contents of COM and POM decreased by burning in both of Bur L and Bur S. Only in Bur L, C and N contents of MOM decreased due to high burning intensity. The C contents of COM, POM decreased by burning in Bur L were gradually restored after 1- and 2-year cropping. The decreased COM-C and POM-C in Bur S were restored only after 2-year cropping. On the other hand, the N contents of POM increased in Bur L after 1- and 2-year cropping, and in Bur S after 2-year cropping although SN did not increased in either Bur L or Bur S. Carbon and N contents of COM, POM and MOM during fallow in Bur L and Bur S are shown in Fig. 4.10. The C and N contents of COM, POM and MOM were not restored during fallow after any copping periods in either Bur L or Bur S.

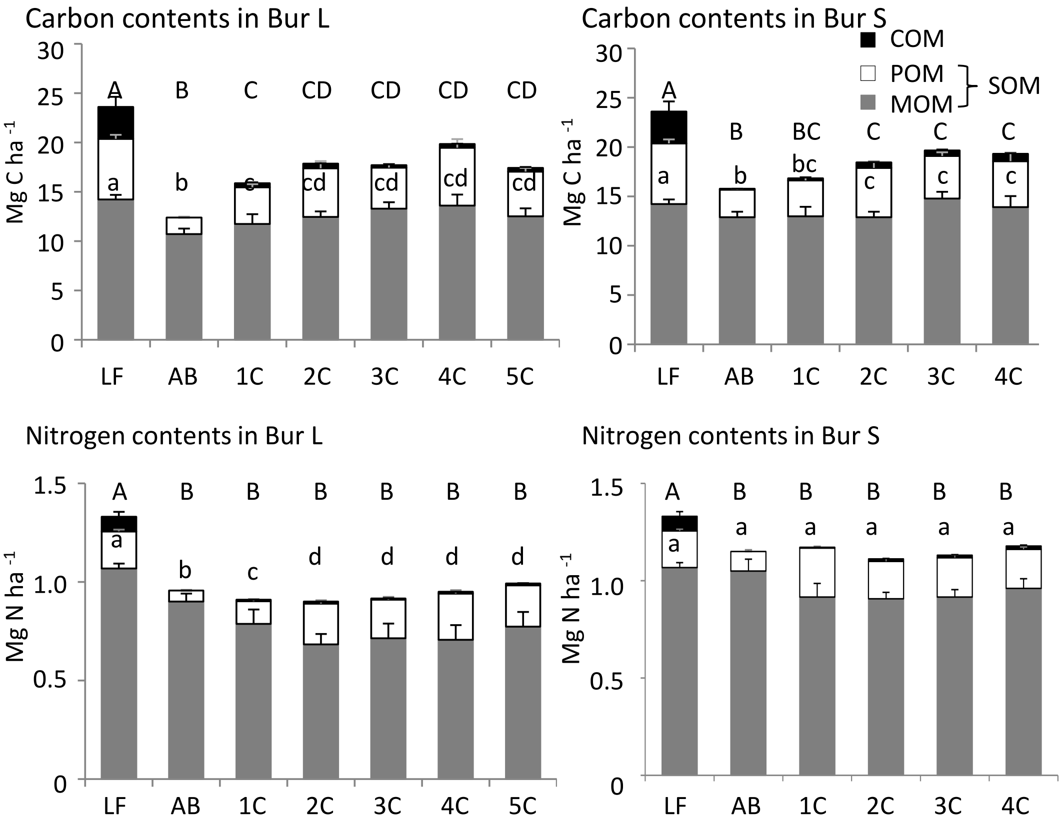
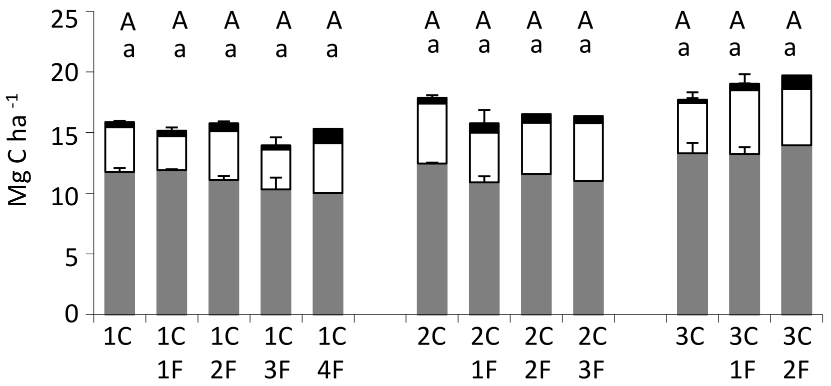
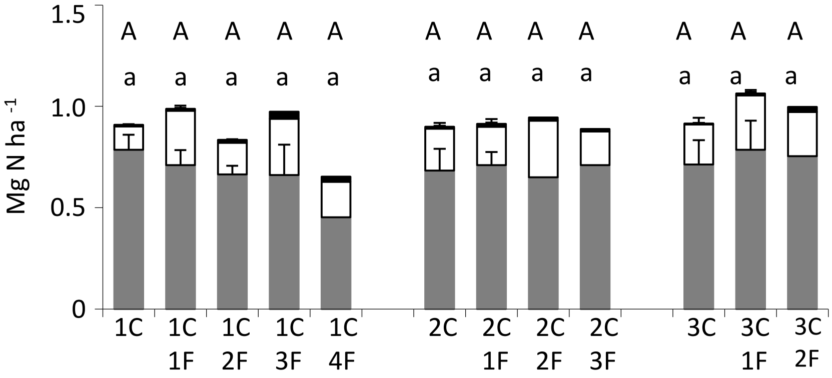


Fig. 4.9
Carbon and N contents of COM, POM and MOM during cropping in Bur L and Bur S.
LF and AB represent long fallow and after burning, respectively. Bars indicate the standard error (*n*=3). Different uppercase letter (A,B,C) indicates that the means of SOM are significantly different ($P < 0.05$). Different lowercase letter (a,b,c,d) indicates significant difference of the means of sum of COM and POM ($P < 0.05$).

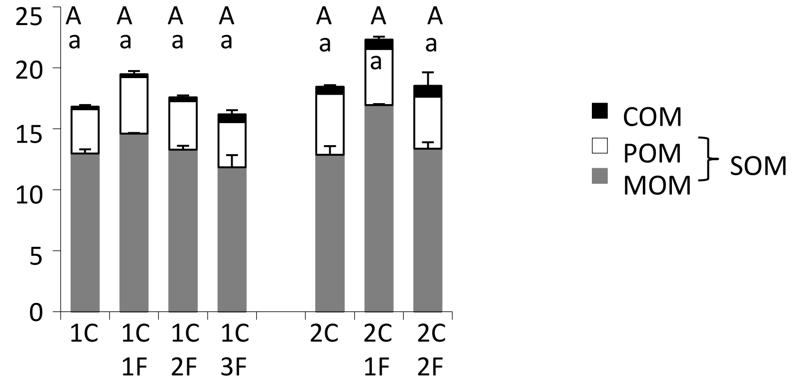
Carbon contents in Bur L



Nitrogen contents in Bur L



Carbon contents in Bur S



Nitrogen contents in Bur S

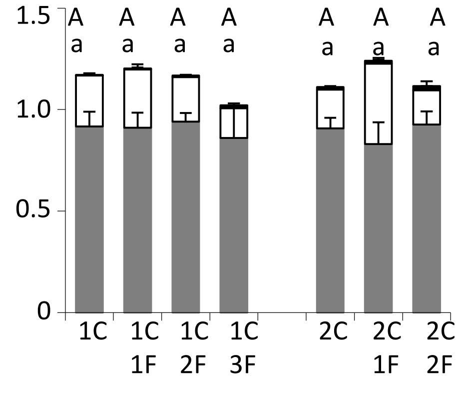
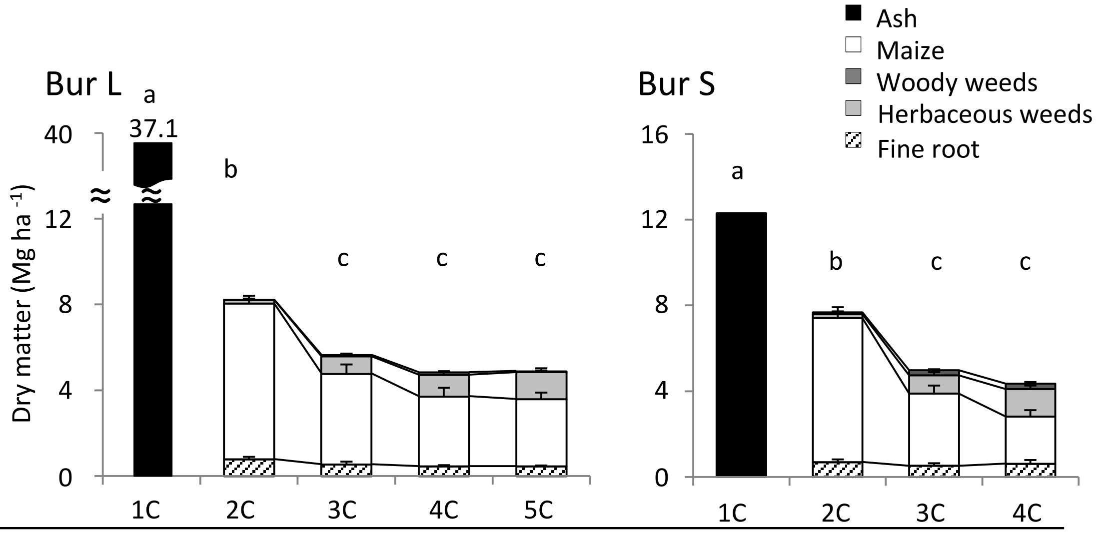


Fig. 4.10

Carbon and N contents of COM, POM and MOM during fallow in Bur L and Bur S. Bars indicate the standard error (n=3). Different uppercase letter (A) indicates that the means of SOM are significantly different ($P < 0.05$). Different lowercase letter (a) indicates significant difference of the means of sum of COM and POM ($P < 0.05$).

4.3.8. Vegetation and input of plant materials in burned spots

The amount and composition of input in Bur L and Bur S during cropping is shown in Fig. 4.11. The amount of ash produced by burning could be considered as input in 1-year cropping, and higher in Bur L than that in Bur S, 37.1 Mg ha^{-1} and 12.3 Mg ha^{-1}, respectively. The amount of input returned to soil was significantly higher in 2- and 3-year cropping in Bur L and 2-year cropping in Bur S compared to Unburned ($P <$ 0.05, Figs. 4.6 and 4.11) due to high production of maize stover by burning. The decrease in woody weeds by burning did not change during cropping in Bur L, while woody weeds gradually increased in Bur S. On the other hand, herbaceous weed germinated after 2-year cropping in both of Bur L and Bur S. Then, the proportion of woody weeds to total input was lower in Bur L than in Bur S after 3-year cropping (Fig. 4.11).



	Bur L 1C	Bur L 2C	Bur L 3C	Bur L 4C	Bur L 5C	Bur S 1C	Bur S 2C	Bur S 3C	Bur S 4C
Input of C (Mg C ha^{-1})	4.5	3.3	2.5	2.2	1.9	1.5	3.2	2.2	1.9
Input of N (kg N ha^{-1})	9.0	34.5	28.6	25.5	22.8	20.0	34.5	28.6	25.5

Fig. 4.11
The composition and amount of input during cropping in Bur L and Bur S.
C represents cropping and value followed by C shows the cropping period. Bars indicate the standard error (n=3). Different letters indicate that the means of total input are significantly different among the cropping period ($P < 0.05$).

Recovery of woody biomass after returned to fallow is shown in Fig. 4.12. In Bur L, woody biomass did not recover significantly during fallow regardless of the different cropping period before returned to fallow. On the other hand, woody biomass in Bur S recovered while did not change with increase in cropping period before fallow. The recovery of woody biomass in Bur S during fallow was almost same as in fallow after cropping for 3 years in Unburned (Figs. 4.7 and 4.12). The amount of input during fallow in Bur L was about 4–5 Mg ha^{-1} mainly composing of herbaceous litter during 2-year fallow, and 2 Mg ha^{-1} in 3- and 4-year fallow (data not shown). On the other hand, the input in Bur S may be the same as that in fallow after cropping for 3 years in Unburned, considering the result of woody biomass in the both plots.

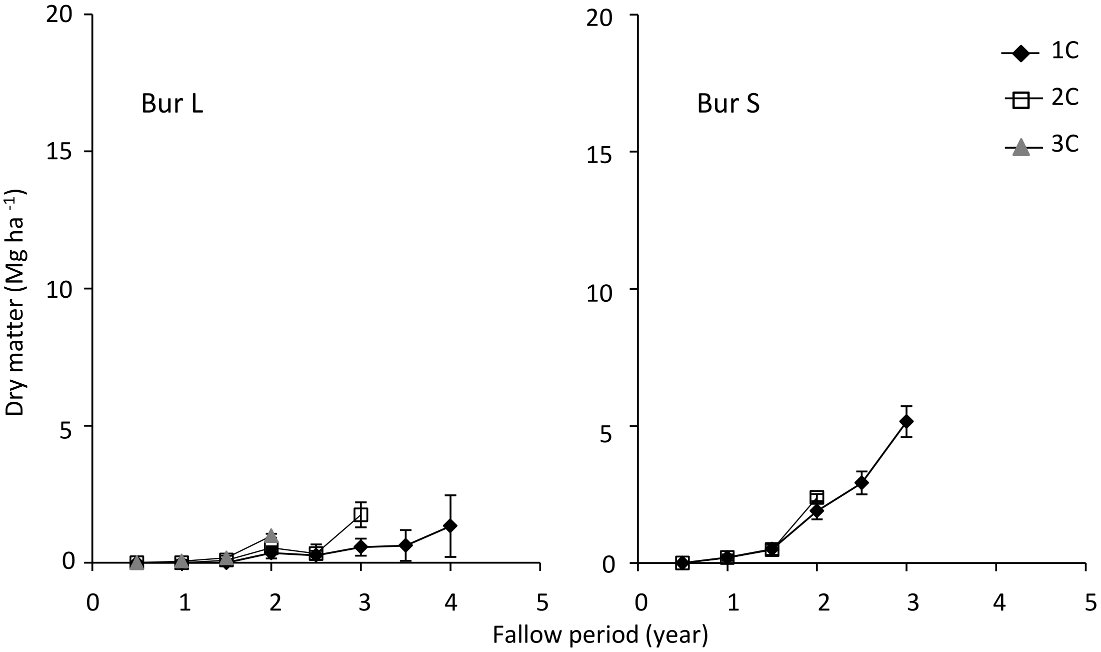


Fig. 4.12
Recovery of woody biomass during fallow after different crop periods in Bur L and Bur S. Bars indicate the standard error (*n*=3). C represents cropping and value followed by C shows the cropping period.

4.4. Discussion

4.4.1. Effects of cropping and short fallow rotation on the composition and amount of plant-material input in unburned spots

The highest input of plant materials returned to soil was in 1-year cropping and it decreased rapidly in 2-year cropping, and the input during 2 to 5 years decreased gradually but not significantly (Fig. 4.6). A significantly low input was found after 10 years cropping (Fig. 4.6), which may be caused by the loss of soil nutrients through years of harvesting (Huggins et al., 1998). The proportion of woody weeds to total input became significantly lower even from 2-year to 5-year cropping (Fig. 4.6), and became negligible after 10-year cropping. The decreases in woody weeds were likely due to the decline of coppicing ability of tree roots or stumps (Luoga et al., 2004) and are in agreement with a study in Malawi, in an area covered by miombo woodland where woody weeds decreased after 30 years of cropping (Walker and Desanker, 2004).

During fallow in Unburned, the composition and amount of input changed with recovery of the woody biomass. During short fallow, even with the increase in previous cropping period from 1 to 2 years, the recovery of woody biomass decreased rapidly (Fig. 4.7). The reason for the clear effect of short cropping on recovery of woody biomass in short fallow may come from the small variability of vegetation inside the experimental site and the separation of the previous cropping period for every 1, 2, 3, 10 and 40 years. In Madagascar, Randriamalala et al. (2012) compared the recovery of woody biomass among fallow for 6 to 10 years after short cropping (1–2 years), middle cropping (3–4 years) and long cropping (5–15 years). The recovery of woody biomass decreased by 12% and 30% in fallow after middle and long cropping, respectively, compared with after short cropping, but not significantly. Under shifting cultivation, woody biomass decreased only after three times of cropping short-fallow rotation (Sovu et al., 2009; Styger et al., 2009). At the different elevation ranges, no coherent effect of previous cropping on recovery of woody biomass was found (Mwampamba and Schwartz, 2011).

In 1-year fallow after short cropping in Unburned, the amount of input decreased because only woody litter was returned, not the stems, while it did not change in 1-year fallow after long cropping because of the few woody weeds (Figs. 4.7 and 4.8). In fallow with a predominance of woody plants, Aweto (1981) found that the input became higher than in cropland only after fallow for 7 years when woody biomass increased. Only in 2-year fallow after 3-year cropping, did the amount of input increase in this study (Fig. 4.8). This was due to the accelerated growth of herbaceous plants because of the decreased competition with woody plants (Fig. 4.7). This has also been reported in Thailand (Funakawa et al., 2006) and Ghana (Adiku et al., 2008).

In response to the retarded regeneration of woody plants, the composition of input changed during the cropping and short fallow rotation in Unburned (Fig. 4.8). The proportion of woody litter to total input decreased during short fallow with an increase in cropping period. Randriamalala et al. (2012) also reported that in fallow for 6 to 10 years, herbaceous litter became predominant with an increase in cropping period before fallow.

The changes in composition could affect the SOM because the different plant materials have different responses against decomposition by microbes. With any land use, maize stovers were decomposed rapidly and woody weed or litter, slowly. However, herbaceous weeds or litter decomposed rapidly only in cropland (Table 4.1), which indicated that the decomposition of herbaceous weeds or litter could be changed with land use possibly through the changes in soil temperature and way of incorporation. Therefore, decomposition rate could be affected not only by their chemical properties such as CN ratio but also environmental factors (Mafongoya and Nair, 1996).

4.4.2. Effects of cropping and short-fallow rotation on soil organic matter through the changes of plant-material input in unburned spots

During short cropping in Unburned (1 to 5 years), SOC (<2000 μm) did not decrease (Fig. 4.4) the amount of input returned to soil did not decrease significantly (Fig. 4.6). There is the possibility that the amount of input C may be able to offset the loss of C from decomposition or leaching (Sugihara et al., 2012). In Zambia, when the period of dry season was 6 months; SVW was low (Fig. 4.2) which could have retarded the decomposition of organic matter (Nhantumbo et al., 2009; Sugihara et al., 2012; Moyano et al., 2013). Zingore et al. (2005) showed that SOC declined gradually with return of crop residue during short cropping in southern Africa, while the 30% decline of SOC was found without return of crop residue. Although large amounts of input was incorporated into soil in 1-year cropping, SOC did not increase (Fig. 4.4) partly because of the increase in decomposition as the input increased (Huggins et al., 1998).

The COM-C composed of the fragmented plants (>2000 μm) did decrease after 1-year cropping (Fig. 4.4) as they could turn over within one year in cropland (Balesdent, 1996). After that, COM-C and POM-C composed of macro-organic matter in various stages of decomposition (53–2000 μm) decreased gradually during cropping from 2 to 5 years but not significantly (Fig. 4.4). The gradual decrease in POM-C was partly due to breakdown of soil aggregates by plowing (Ouattara et al., 2006). The gradual decrease in COM-C and POM-C seemed to be coherent with the gradual decrease in the input and the decrease in the proportion of woody weeds which was decomposed more slowly than herbaceous weeds and maize during cropping (Fig. 4.6). Furthermore, decomposition was enhanced by an increase in microbial activity with the rise in average daily soil temperature during the rainy season from 23.9°C in long fallow to 25.5°C in cropland (Fig. 4.2) (Tinker et al., 1996; Jobbagy and Jackson, 2000). Thus, COM-C and POM-C might be more susceptible to plowing and changes in amount or composition of input compared to MOM-C (<53 μm) which includes organo-mineral complexes (Christensen, 1992; Balesdent et al., 1998; Chivenge et al., 2007). Solomon et al. (2000, 2002) reported that POM-C declined by 63% and 79% with 3-year cropping in Tanzania and 30-year cropping in Ethiopia, respectively, although SOC declined only by 56% and 44%, respectively.

The significant decrease in SOC after 10-year cropping was not restored during 2-year fallow (Fig. 4.5) because the input did not increase after returned to fallow. Aweto (1981) also reported that SOC was not restored within 3-year fallow after 50% SOC loss by cropping due to low inputs. However, the amount of input during fallow after short cropping became lower compared with those in cropland (Fig. 4.8) but COM-C and SOC did not decrease during the fallow (Fig. 4.5) due to the input of woody and herbaceous litter. The decomposition of woody litter and herbaceous litter (Table 4.1) was constrained because leaving plant litter on the soil surface decreases its accessibility to microbes (Six et al., 1998; Promsakha et al., 2005), and the lower temperatures caused lower microbial activity (Tinker et al., 1996; Jobbagy and Jackson, 2000).

Only POM-C increased especially in the second year of fallow after 3- and 10-year cropping (3C2F and 10C2F) (Fig. 4.5). The highest accumulation of POM-C in 3C2F was reflected from the highest input (Fig. 4.8). Thus, input C was retained in the POM-C fraction during fallow due to leaving the plant litter on the soil surface and the formation of soil aggregates (Balesdent, 1996; O'Brien and Jastrow, 2013). Sarmiento and Bottner (2002) also reported that the fallow period leads to an increase in the C contents of labile SOM pools.

On the other hand, SN did not decrease significantly with short cropping partly because of the small output of N such as harvested grain N and leachate N (Zingore et al., 2005). The small output may be attributed to restricted mineralization of SOM to inorganic N during dry season (Fig. 4.2). During short cropping COM-N decreased but POM-N did not (Fig. 4.4), while Solomon et al. (2000) reported that POM-N decreased within 3-year cropping without input of residue in Tanzania. These contrasting results suggested that plant absorbed N from COM or POM fraction and in turn the plant materials returned to soil could be retained in fraction of POM. The significantly decreased SN after long cropping was not restored during 2-year fallow (Fig. 4.5) partly because of low litter input which could redistribute N from deeper soil via woody plant uptake (Szott et al., 1999).

4.4.3. Effects of cropping and short fallow rotation on the composition and amount of plant-material input in burned spots

The larger amount of the input composed of ash or maize stover lasted for 3 years in Bur L and for 2 years in Bur S (Fig. 4.11). High production of maize stover was attributed to the abundance of available nutrients degraded from SOM by burning (details in Chapter 3, Tables 3.3 and 3.5), which were also reported in Southeast Asia (Funakawa et al., 2006), South America (Silva-Forsberg and Fearnside, 1997) and Central Africa (Okore et al., 2007).

Although the composition of input was same in 1 and 2-year cropping between Bur L and Bur S (Fig. 4.11), it became different after 3-year cropping. The herbaceous weed decreased by burning could germinate in 2-year cropping in Bur L and Bur S (Fig. 4.11), which were brought via seed dispersal by wind from surrounding unburned field. On the other hand, almost no woody weeds could establish in Bur L (Fig. 4.11), indicating that the fire intensity in Bur L was lethal for tree coppicing ability (De Castro and Kauffman, 1998). As a result, the weed composition after 3-year cropping was only herbaceous in Bur L and herbaceous and woody in Bur S.

During fallow after cropping in Bur L and Bur S, the woody biomass could recover only in Bur S (Fig. 4.12). The vegetation in Bur L during short fallow after any cropping period was only herbaceous biomass because of no woody biomass (data not shown for herbaceous). D'oliveira et al. (2011) also reported that the woody biomass recovery during fallow became slow with increase in fire intensity in Amazon.

4.4.4. Effects of cropping and short-fallow rotation on soil organic matter through the changes of plant-material input in burned spots

Although the COM and POM decreased by burning both in Bur L and Bur S (Fig. 4.9), MOM decreased only by high burning intensity (Bur L) which could disrupt the physicochemical protection of organic matter by clay minerals (Bird et al., 2000).

The decreased C contents of POM (POM-C) by burning gradually recovered during cropping (Fig. 4.9) although the cropping could facilitate the SOM decomposition via increase in microbial activity with higher soil temperature (Fig. 4.2) (Tinker et al., 1996; Jobbagy and Jackson, 2000). The recovery of the POM-C might be derived from high amount of input as ash in 1-year cropping and maize stover in 2-year cropping in Bur L, and maize stover in 2-year cropping in Bur S. Other studies under slash-and-burn agriculture also reported the increase in SOC during cropping with the input of ash (Kauffman et al., 1993; Kendawang et al., 2004, 2005; Strømgaad, 1992; Tanaka et al., 2004). The restoration of POM-C during cropping might be also attributed to restricted decomposition by return of the recalcitrant plant materials in ash in 1-year cropping and the maize stem in 2-year cropping which became harder as the biomass increased to sustain standing (Fig. 4.11). After returned to fallow, COM-C, POM-C and MOM-C did not increase in either Bur L or Bur S (Fig. 4.10), regardless of the cropping period before returned to fallow. Thus, the input returned to soil might be equal to output such as decomposition and leachate during fallow, suggesting that short fallow could not be enough periods for restoration of SOC. Roder et al. (1997) also reported that the decreased SOC by burning did not change during short fallow for 1 to 3 years.

Contrary to the recovery of SOC during cropping, SN did not recover in either Bur L or Bur S (Fig. 4.9), but not decrease significantly despite N output via harvesting grain. Because the ash contained little N of 9 kg ha^{-1} and 20 kg ha^{-1} in Bur L and Bur S, respectively (Fig. 4.11), it could not lead to increase in SN. Further analysis is necessary on the balance of N input and output in Bur L during cropping. On the other hand, the proportion of POM-N increased gradually during cropping in Bur L (Fig. 4.9), which was attributed to the redistribution of N from mineralized N from MOM or deeper soil horizon through the input of plant materials. The increase in POM-N after 1- and 2-year cropping in Bur L (Fig. 4.9) was attributed to maize root decomposed during rainy season in 1-year cropping and large amount of maize stover returned to soil in 2-year cropping (Fig. 4.11). The redistribution of N from MOM to COM and/or POM through the input of plant materials in Bur L was enhanced by degradation or disruption of MOM-N by intensive burning (Mills and Fey, 2003, 2004). The degraded MOM-N might be absorbed more easily by plant. After returned to fallow for 1 to 3 years, SN was not restored (Fig. 4.10). Short fallow was not adequate period for the restoration of SN because of the low woody biomass (Fig. 4.12) which could not redistribute N from deep horizon to surface soil via litter deposition (Szott et al., 1999). Therefore, restoration of SN may need longer period in Bur L than in Bur S because woody biomass rarely recovered during short fallow in Bur L.

4.4.5. Comparison of unburned and burned spots

The changes of SOM during cropping and fallow were different with fire intensity because of different amount and composition of input returned to soil. The only labile fraction C decreased by short cropping in Unburned could restored during 2-year fallow after 3-year cropping reflected the large amount of input. The decreased SOC and labile fraction by burning in Bur L and Bur S even restored during cropping because of large amount of low decomposable input returned to soil. Although SN did not change significantly in all the treatments, the proportion of POM-N and/or COM-N increased gradually during cropping only in Bur L. Plant could absorb N mainly from POM or COM fraction in Unburned and Bur S, while plant could absorb N not only from POM or COM but also from MOM fraction in Bur L, reflecting degradation of MOM with high soil heating. The changes of soil C and N stock will be validated in Chapter 5 by measurement of input C and N and the loss of C through the decomposition and leaching, and N loss via leaching and plant uptake.

From the results of woody biomass during fallow (Figs. 4.7 and 4.12), the recovery of woody biomass during fallow after 1- and 2-year cropping in Bur S was almost same as that after 3-year cropping in Unburned. It is indicated that the extent of decrease in coppicing ability was same between 3-year cropping and burning of bush trees.

4.5. Conclusion

During short cropping in Unburned, SOM and grain yield did not change. The prolonged dry season could constrain the decomposition of SOM due to low soil moisture content. However, labile fraction of COM-C and POM-C decreased gradually because of decrease in proportion of woody weeds decomposed slowly. The low decrease in SN and POM-N might be attributed to the low maize production and leachate. After returned to fallow, only POM-C could recover in fallow after 3- and 10-year cropping because of the high input of litter and retarded decomposition with leaving plant litter on the surface. Decrease in SN by long cropping did not recover in short fallow because of low woody plant which could not redistribute N from deeper soil via litter fall.

On the other hand, the high maize yield lasted for 2 years in Bur L and for 1 year in Bur S. Decreased C contents of all the soil fractions by burning tend to recover during short cropping in Bur L, while only labile soil fractions C decreased and recovered gradually in Bur S. It reflected large amount of input as ash and maize stem returned to soil in 1- and 2-year cropping. Although SN decreased by burning did not change during short cropping in Bur L and Bur S, POM-N recovered during cropping in Bur L partly due to the redistribution of N from MOM fraction via input of plant materials. After returned to fallow, the C and N contents of all the fractions did not change irrespective of fire intensity.

The spatial variability of the SOM and woody biomass induced by burning was still high after cropping and short fallow. Recovery of woody biomass decreased with increase in previous cropping period and fire intensity. At the unburned spots, 2-year fallow after 3-year cropping is relatively sustainable management in terms of maintenance of POM, SOM and grain yield in case of the cropping after clearing long fallow. On the other hand, SOM including labile soil fraction could not recover during short fallow at the burned spots. Although the SOM decreased by burning rapidly, the rate of decrease in SOM was slow during short cropping in whole the cleared field.

Chapter 5

Soil carbon and nitrogen budgets during cropping and short-natural fallow rotation

5.1. General

In Eastern Province Zambia, rapid conversion of long fallow to cropland followed by shortening fallow may cause a decrease in soil C and N stocks (Jaiyeoba, 2003; Walker and Desanker, 2004; Okore et al., 2007; Mapanda et al., 2013). Several studies have claimed that the short fallow was not enough to recover the decrease in soil C and N stocks by cropping and/or burning (Brady, 1996; Mertz, 2002; Hauser et al., 2006). However, it depends on the extent of decrease in soil C and N stocks and vegetation during cropping and/or burning before fallow (Mobbs and Cannell, 1995; Hauser et al., 2006), which has been rarely reported. In this region, although the only labile soil C stock decreased during short cropping, that could be restored during short fallow for 2 years after 3-year cropping at the unburned spots (Chapter 4). On the other hand, the decrease in soil C and N stock by burning and/or cropping for 10 years could not be fully restored during fallow for 2 years (Chapter 4). Since those changes in soil C and N stocks during cropping and fallow are the result of the budget of input to soil and output from soil, it is important to validate the restoration of soil C and N stock by the C and N budgets between input to soil and output from soil during cropping and short fallow rotation (Paustian et al., 2000; Whitbread et al., 2005).

The C budget can be estimated from the output flow from soil via CO_2 flux as a result of microbial respiration (decomposition of organic matter) and C leaching, and input flow via rainfall and plant materials returned to soil (Funakawa et al., 2006; Sugihara et al., 2012). In semiarid tropics, the CO_2 flux expresses seasonal fluctuation mainly in accordance with that of soil moisture, the main controlling factor of microbial activity (Mapanda et al., 2010; Sugihara et al., 2012). Thus, annual CO_2 flux could be estimated reasonably by calibrating occasional CO_2 flux measurement with continuous data of soil moisture content over the season. The N budget can be estimated from the output flow from soil via N leaching, denitrification, and harvested grain or woody increment, and the input flow to soil via rainfall, litter fall and N fixation. In semiarid tropics, little denitrification was reported in unburned and burned places (Andersson et al., 2004; Mapanda et al., 2012), and the leguminous trees in miombo woodland could fix little N (Högberg, 1986). The amount of N leachate depends on the mineralization of soil N stock (Fujii et al., 2013) and the root development (Chikowo et al., 2004). It indicates the importance of leaching measurement in all the fields where the different extent of the mineralization and root development exist.

The objectives were to evaluate the soil C and N stocks under different cropping periods followed by short fallow at unburned and burned spots by a budget analysis using quantitative measurement of each input and output flow.

5.2. Materials and methods

5.2.1. Experimental design

Cropping plots consisting of spots unburned (Unburned) and spots burned with emergent tree (Bur L), and fallow plots consisting of only Unburned were used as described in Chapter 2. Because the area of Bur L in the fallow plots was too small to conduct the following measurements, Bur L in the fallow plots was not considered in this Chapter. The treatments in 2009/2010 were composed of cropping for 1-, 2- and 3-year cropping (1C, 2C, 3C) at Unburned and Bur L, fallow for 1-year after 1- and 2-cropping (1C1F, 2C1F), fallow for 2-year after 1-year cropping (1C2F) in Unburned. The treatments in 2010/2011 were composed of cropland in Unburned and Bur L of 1C, 2C, 3C, 4C, and fallow in Unburned of 1C1F, 2C1F, 3C1F, 1C2F, 2C2F, 1C3F. The treatments in 2011/2012 were composed of cropland in Unburned and Bur L 2C, 3C, 4C, 5C, and fallow in Unburned of 1C2F, 2C2F, 3C2F, 1C2F, 2C3F, 1C4F.

5.2.2. Measuring environmental factors

From November 2010 to October 2011, soil temperature at a depth of 5 cm was monitored in every 20 minutes in cropland (Unburned and Bur L) and long fallow (CS215 thermistor probes connected to a CR1000 data logger; Campbell Scientific, Inc., USA). From November 2010 to October 2011, soil volumetric water content (SVW) at the depth of 0–10 cm was recorded in every 20 minutes in cropland (Unburned and Bur L) and long fallow (Easy AG probe; Sentek pty Ltd., Australia, connected to a CR1000 data logger), and in 1-year cropland at Unburned and Bur L at the depth of 0–5 cm (SM

300 water probe connected to a DL6 data logger; Delta-T Devices, Ltd., England). In November 2008, field infiltration rate was measured in 1- and 2-year cropping at Bur L and Unburned, and 1-year fallow at Unburned by using the Mini-disk infiltrometer (Mini-disk Infiltrometer Model S; Decagon Devices, Inc, USA). This infiltrometer (4.5 cm in diameter; 32.6 cm in length) is portable and can be easily used with a little amount of water (50–90 mL per measurement). In this measurement, the water level of infiltrometer were recorded with time for one to five minutes, and plotted against the square root of time.

5.2.3. Measuring CO_2 efflux rate

Soil CO_2 efflux was measured in all the treatments of cropping at both of Unburned and Bur L, and fallow only at Unburned for 5 times in 2009/2010, and for 13 times in 2010/2011, and for 7 times in 2011/2012. Three plastic collars with the diameter of 20 cm and the height of 20 cm were inserted at the depth of 0–15 cm (main rooting zone) at each measurement location one week before the first measurement. All the collars were re-installed within a plot every year prior to cropping season. As soil respiration consists of plant-root respiration and microbial respiration, the plant-root respiration was excluded by the trenching method according to Shinjo et al. (2006) as follows. The enclosed soil within the collar was later covered with a fine plastic mesh to support the soil in the collar and to maintain the same soil moisture condition as outside the collar which was confirmed by Sugihara et al. (2012). For each measurement, to block CO_2 evolved from plant root respiration, the collar was removed and the bottom of the collar was covered by a plastic sheet, and then the collar was put in the hole again. After placement on a collar, CO_2 efflux rate was measured by a closed-chamber system with an infrared gas analyzer (LI-8100; LI-COR Inc., Lincoln, NE). Measurement was repeated three times at each collar for every measurement.

5.2.4. Sampling and analysis of drainage water and rainfall

Capillary lysimeters (Daiki Rika Kogyo Co., Ltd., Japan) were installed in the same plots for CO_2 efflux measurement in November 2010. Structure of the lysimeter is shown in Fig. 5.1. The lysimeter with the dimension of 35 cm in depth× 25 cm in width × 20 cm in height was installed at the depth of 15–35 cm with three replicates in each treatment. Percolated water in the lysimeter was drained at depth of 30–35 cm via capillary (polyester, pore radius of capillary of 1.85×10^{-5} m). Dug up soils were backfilled *in situ* horizon to the lysimeter. To catch all the percolated water, the capillary lysimeter was buried with incline of two to three degrees (Fig. 5.1). The water was trapped into a sampling bottle in a bucket via sampling pipe. Rainfall collectors consisted of a 18 cm diameter funnel attached to the collection bucket. The top of the funnel was covered with nylon 2-mm mesh. Samples of percolated water and rainfall were collected twice per month and once per month, respectively, in 2010/2011 and 2011/2012. To inhibit transformation of inorganic N by microbes, a $CuBr_2$ solution (0.05 to 0.10 mg L^{-1} Cu) was added in the sampling bottles as a preservative. The bactericidal effects of this level of Cu ion were confirmed by Fujii et al. (2009). Water samples were filtered through a 0.45 µm filter and stored at 4°C until analyses. Concentration of NO_3–N and NH_4–N of sample water was measured by high performance liquid chromatography (HPLC; ion chromatograph HIC-6A, Shimadzu; shim-pack IC-C3 for NH_4^+, shim-pack IC-A1 for NO_3^-, conductivity detector CDD-6A), and concentration of total N and total C was measured by TOC-N auto-analyzer (TOC-V carbon analyzer with an IN unit; Shimadzu, Japan).

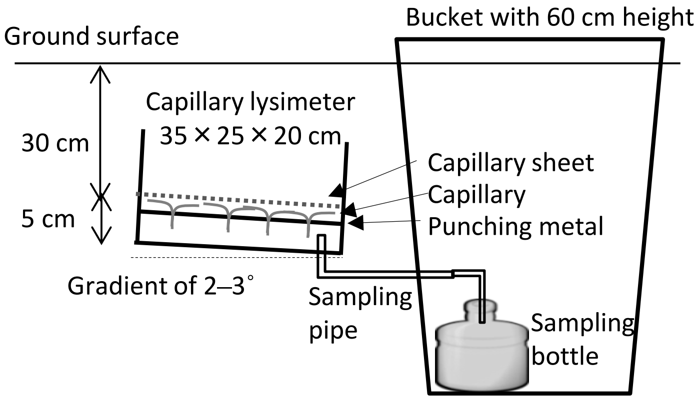


Fig. 5.1
Structure of capillary lysimeter.
A collection space of lysimeter was 5 cm at the depth of 30–35 cm.

5.2.5. Samplings and analysis of soil and plant materials

The same samples of soil at the depth of 0–15 cm, above ground biomass and root biomass were used which were collected in Chapter 4 (Table 4.1). All the samples of soils and plant materials were ground to fine powder by ball mill (PM 200; Retsch GmbH, Germany) and the C and N contents of those samples were analyzed by dry combustion method with a NC analyzer (Vario Max CHN; Elementar, Germany).

5.2.6. Data analyses

All statistical analyses were performed with Sigma plot 11.0 (SYSTAT Software Inc., CA, USA). All data were expressed on a dry weight basis. For data in cropland, one-way analysis of variance (ANOVA) was used to detect the significant differences of variables. Differences between treatments in fallow were tested by a two-way ANOVA (cropping period before fallow × fallow period). When ANOVA indicated significant differences, mean comparisons were performed with the Tukey Kramer multiple comparison test. In all cases, $P < 0.05$ was considered significant.

To estimate the annual CO_2 flux from the field data, a modified Arrhenius relationship were used: $C_{em} = a M^b \exp(-E/RT)$, where C_{em} is the hourly CO_2 efflux rate (mg CO_2–C m^{-2} h^{-1}), M is the volumetric soil water content (L L^{-1}), E is the activation energy (J mol^{-1}), R is the gas constant (8.31 $Jmol^{-1}K^{-1}$), T is the absolute soil temperature (K), a and b is a constant (Shinjo et al., 2006). The equation can be rewritten in logarithmic forms: $\ln C_{em} = \ln a + b \ln M - E/RT$. A series of coefficients, a, b and E, were determined by stepwise multiple regression analysis ($P = 0.05$) for each treatment.

As the annual output from soil, decomposition of organic matter (CO_2 efflux) and C leaching, and as the annual input to soil, plant materials returned to soil and rainfall were considered to estimate annual C budget. In cropland, as the annual output of N from soil, harvested grain, plant uptake (roots, weeds and maize stover) and leaching, as the annual input to soil, rainfall and the plant materials returned to soil (roots, weeds and maize sotver), were considered to estimate the annual N budget. In fallow, as the annual output of N from soil, plant increment (roots, woody and herbaceous) and leaching, as the input to soil, litter (roots, woody and herbaceous) and rainfall, were considered to estimate the annual budget of N. Annual budget was calculated from November in 2010 to October in 2011 and November in 2011 to October in 2012.

5.3. Results

5.3.1. Soil C and N stocks

The soil C and N stocks did not decrease at Unburned by cropping for 1 to 5 years apparently (Fig. 5.2). The soil C stock decreased by burning was restored partly during cropping while soil N stock decreased by burning did not change. After returned to fallow, the soil C and N stock did not change at Unburned and Bur L significantly.

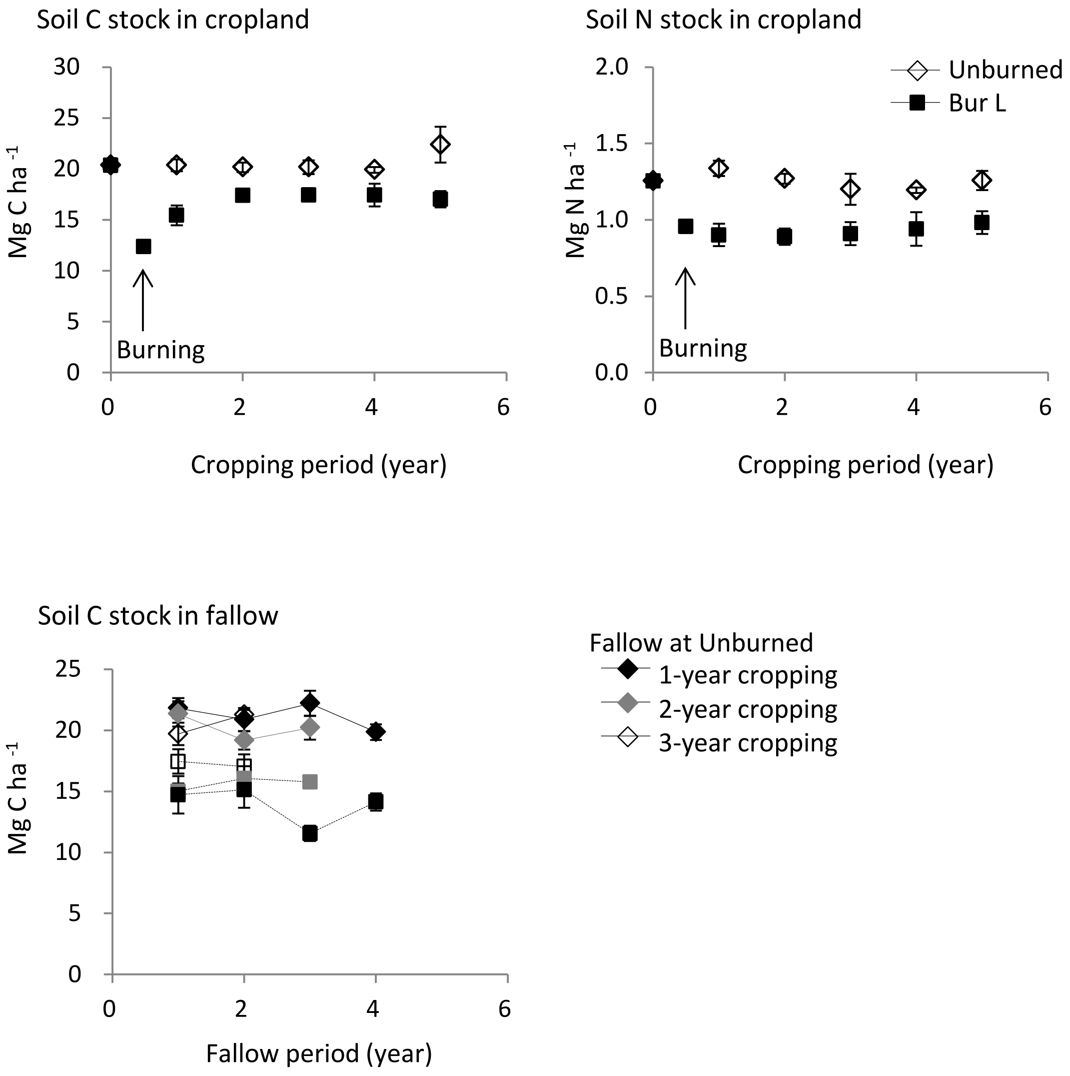


Fig. 5.2
Soil C and N stock during cropping and fallow at Unburned and Bur L.
Bars indicate the standard error (5C, 1C4F, 2C3F, 3C2F for *n*=3, others for *n*=6).

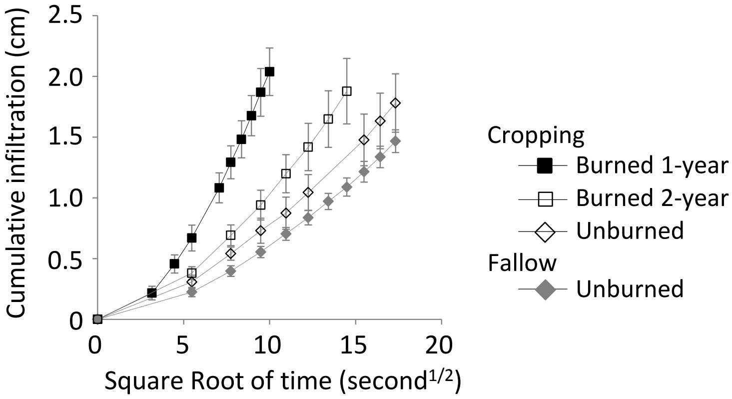


Fig. 5.3
Infiltration rate in Unburned and Bur L. Bars indicate standard error (*n*=3).

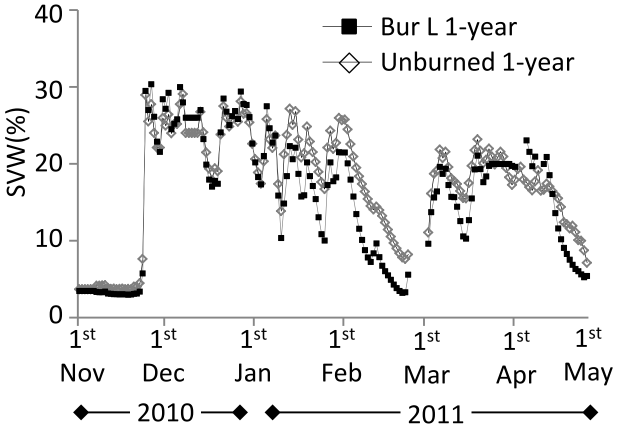


Fig. 5.4
Soil volumetric water contents (SWW) at 0-5 cm of 1-year cropping in Bur L and Unburned in 2010/2011.

5.3.2. Environmental factors

In 1-year cropping at Bur L, the field infiltration rate was much faster than in the others (Fig. 5.3, $P < 0.05$), and the soil volumetric water content (SVW) at the depth of 0–5 cm was diminished more rapidly after each rainfall event than that at Unburned (Fig. 5.4). Especially after January of 2011, SVW became lower at Bur L than at Unburned (Fig. 5.4). Except for 1-year cropping at Bur L, SVW in rainy season indicated the same fluctuation among all the treatments as shown in Fig. 5.5. Because of dry spell from February to March in 2010/2011, the SVW dropped to under –1.5 MPa in all the plots. The annual average SVW was slightly higher in 2010/2011 (Fig. 5.5) than in 2011/2012 (Fig. 4.2 in Chapter 4). Averaged soil temperature during rainy season in 2010/2011 was 27.2°C at Unburned and Bur L during cropping, and 24.4°C in long fallow. The averaged SVW and soil temperature during dry season was same among the treatments, 3% and 25°C in 2010/2011, respectively.

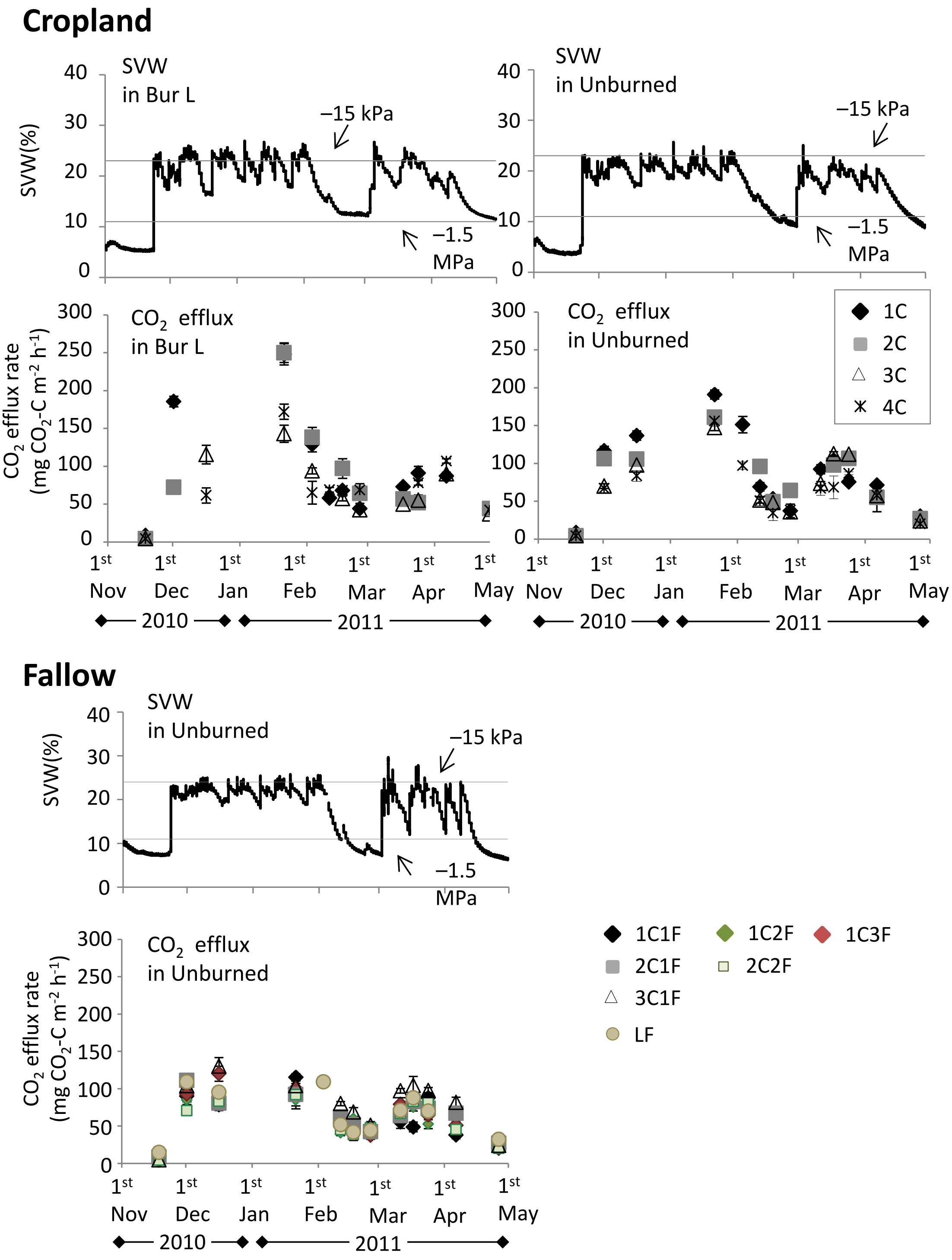
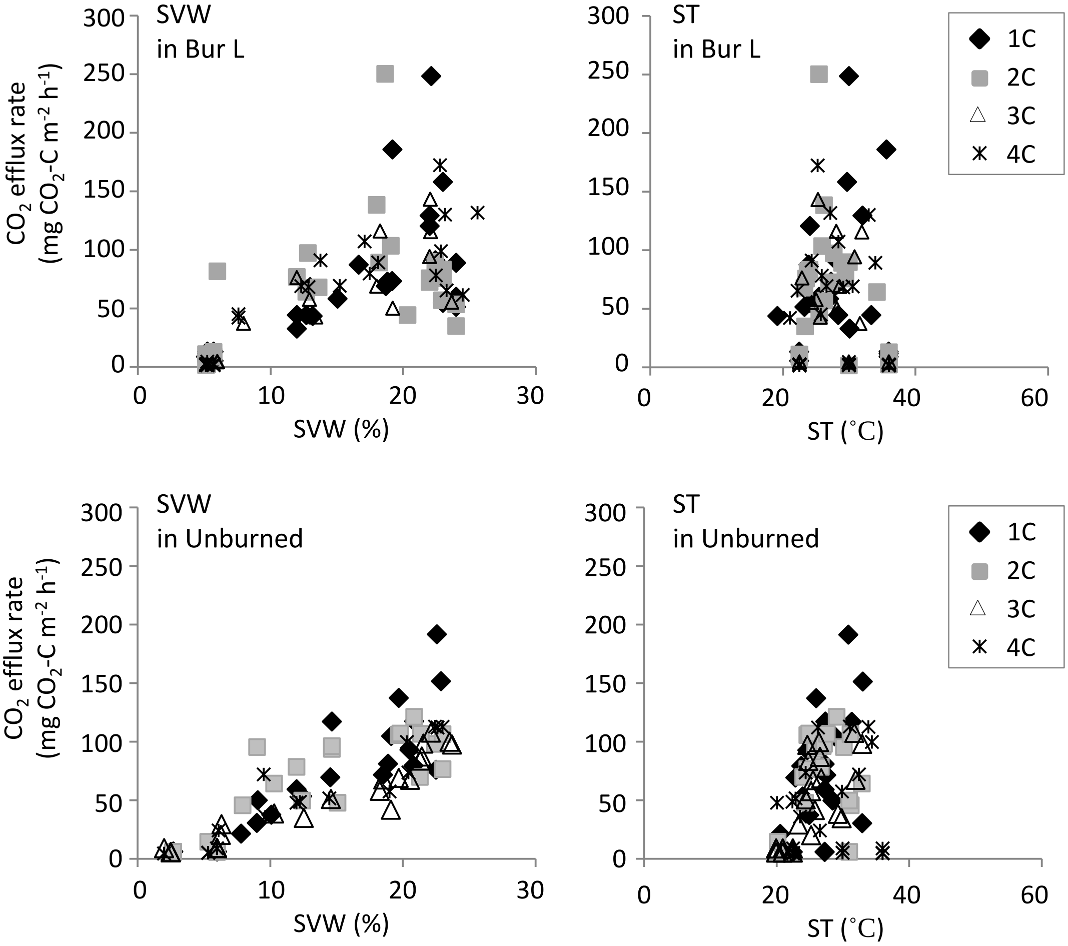


Fig. 5.5
Fluctuation in soil volumetric water content (SVW) and the CO$_2$ efflux in cropland and fallow at Unburned and Bur L during rainy season in 2010/2011. Bars indicate standard error (*n*=3). SVW in cropland shows 4-year cropping in Unburned and Bur L, and SVW in fallow shows LF. LF represents long fallow, C represented cropping and F represents fallow. Value followed by C or F shows the period of cropping or fallow, respectively.

Cropland



Fallow

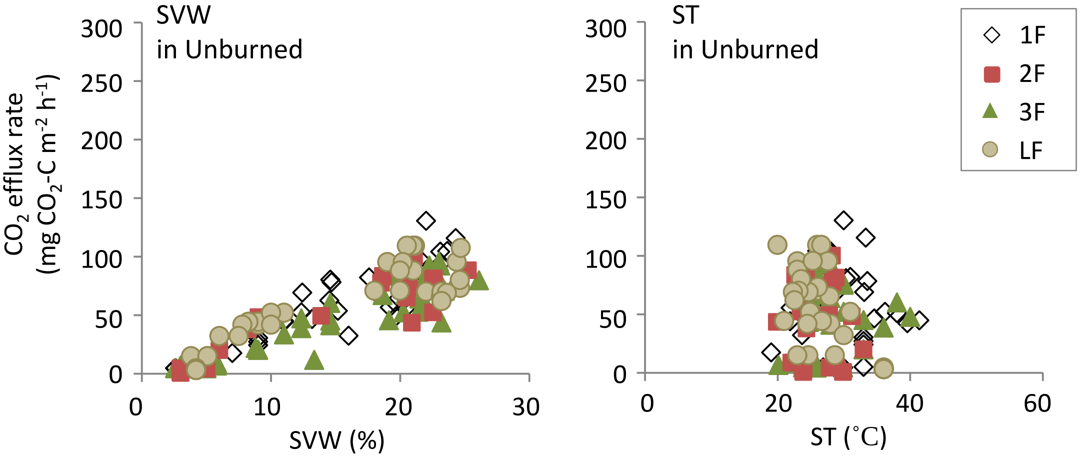


Fig. 5.6
Relationship between the CO$_2$ efflux and soil temperature (ST), soil volumetric water (SVW) content in cropland of Unburned and Bur L, and during fallow of Unburned

5.3.3. Fluctuation and controlling factors of CO_2 efflux from soil

The efflux rate during dry season from May to October during experimental year was as low as 1–6 mg CO_2–C m^{-2} h^{-1} in all the treatments. Fluctuation of CO_2 efflux rate during the rainy season in 2010/2011 is shown in Fig. 5.5. The averaged CO_2 efflux rate during rainy season at Bur L was highest in 1-year cropping (94 mg CO_2–C m^{-2} h^{-1}) partly due to high CO_2 efflux at beginning of December, and became low in 2-, 3- and 4-year cropping, 86, 71, and 79 mg CO_2–C m^{-2} h^{-1}, respectively. At Unburned it was getting lower in order of 1-, 2-, 3- and 4-year cropping, 87, 79, 70, and 64 mg CO_2–C m^{-2} h^{-1}, respectively. In fallow at Unburned, the CO_2 efflux rate became as low as that in long fallow. The averaged efflux during rainy season was not different significantly with fallow periods and cropping periods before fallow, and was 67, 57, 61 and 66 mg CO_2–C m^{-2} h^{-1} in 1-, 2-, 3-year and long fallow, respectively.

The CO_2 efflux rates in all the treatments were correlated significantly with SVW but not with soil temperature, based on the measurements in 3-year experimental period (Fig. 5.6). To consider the effect of land use (burning, cropping and fallowing) and ridging (Fig. 5.5) on the CO_2 efflux estimate, the equation for CO_2 efflux was identified for each treatment by stepwise regression analysis. As a result, the CO_2 efflux was found to be well estimated by only SVW ($P < 0.05$, $r^2 > 0.91$). However, the R square for the estimation of CO_2 efflux in 1-year cropping at Bur L was relatively low ($r^2 = 0.80$).

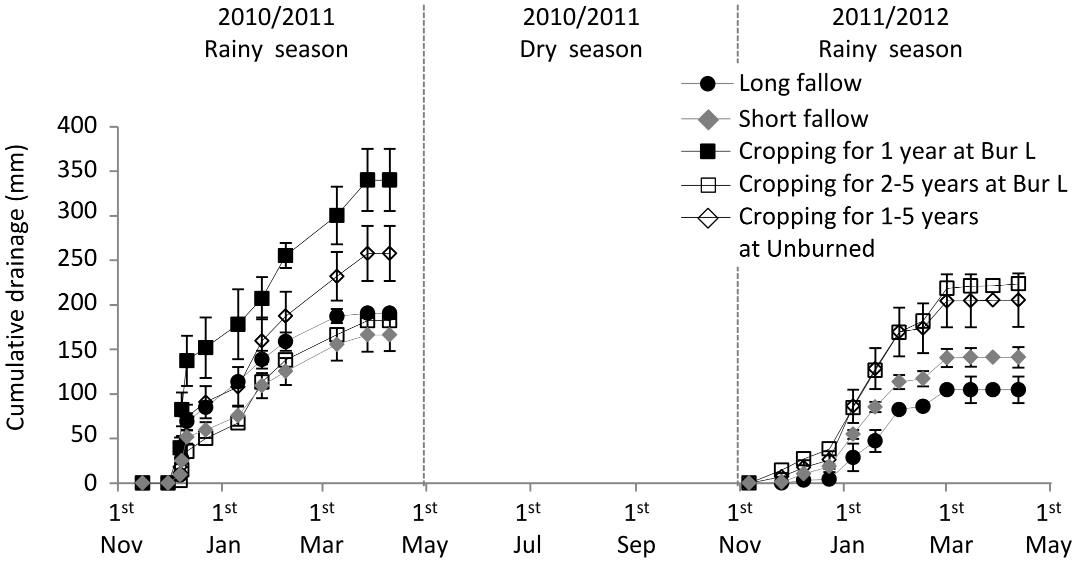


Fig. 5.7
Annual cumulative drainage during cropping at Unburned and Bur L and during fallow in Unburned from November 2010 to May 2012. Bars indicate standard error (*n*=3).

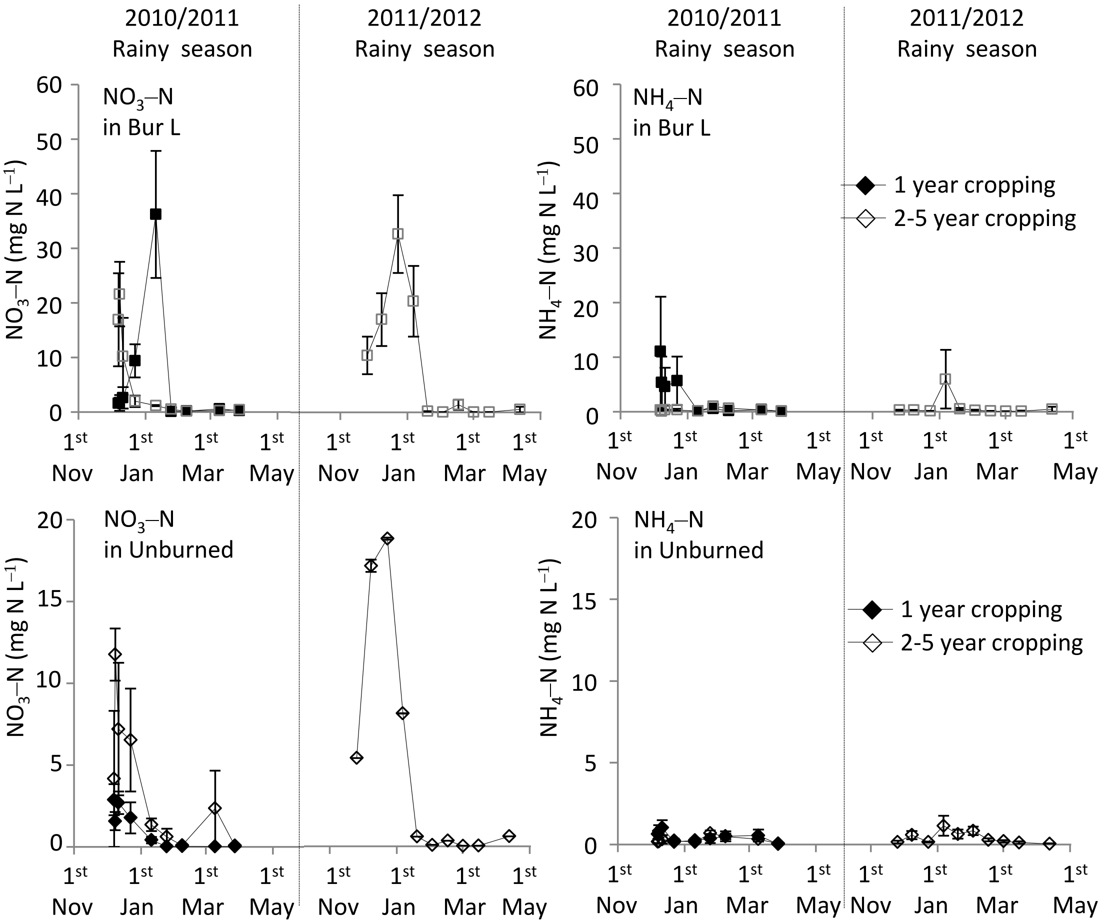
5.3.4. Drainage volume and C and N in leachate

Figure 5.7 shows annual cumulative volume of drainage at the depth of 30 cm. The annual drainage was higher in cropland than in short and long fallow significantly in both years. It was highest in 1-year cropping at Bur L among all the treatments in 2010/2011. Volume of drainage was higher in 2010/2011 than in 2011/2012, but not significantly although annual rainfall was higher in 2010/2011 (1081 mm) than in 2011/2012 (879 mm).

The concentration of total C in leachate was highest in 1-year cropping at Bur L, especially at the first leaching, and not different among other treatments (Appendix I). Because the concentrations of NO_3–N and NH_4–N in leachate was not different significantly among 2- to 5-year of each treatment, that of 1-year and average of 2- to 5 year in cropland at Unburned and Bur L, and fallow at Unburned are shown in Fig. 5.8. The concentration of NO_3–N in leachate in all the treatments was high until beginning of January, while that of NH_4–N in leachate was low through the rainy season except for in 1-year cropping at Bur L. The high NH_4–N concentration followed by the high NO_3–N in 1-year cropping at Bur L became lower in 2- to 5-year cropping. On the other hand, the low NO_3–N concentration in leachate in 1-year cropping at Unburned became higher in 2- to 5-year cropping. After returned to fallow at Unburned, NO_3–N concentration in leachate became low. The NO_3–N in 1-year fallow also became lower in 2- to 4-year fallow. The different cropping periods before fallow did not affect concentration of the NO_3–N in leachate.

The annual cumulative amount of total C and N contents in leachate is shown in Figure 5.9. The annual loss of total C and N via leaching was highest in 1-year cropping at Bur L, mainly derived from the first leaching. The annual C leaching was not different among the other treatments, while that of N was higher in cropping than in fallow. In cropland, the annual loss of N via leaching was relatively larger in 2011/2012 than in 2010/2011.

Cropland



Fallow

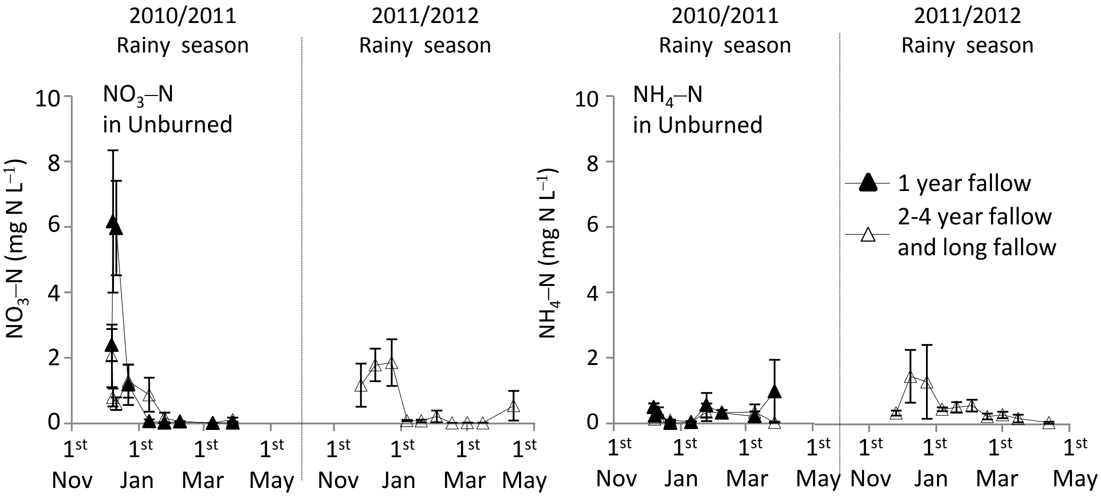


Fig. 5.8
The concentrations of NO_3–N and NH_4–N in leachate during cropping at Unburned and Burned and during fallow in Unburned in rainy season of 2010/2011 and 2011/2012. Bars indicate standard error (*n*=3).

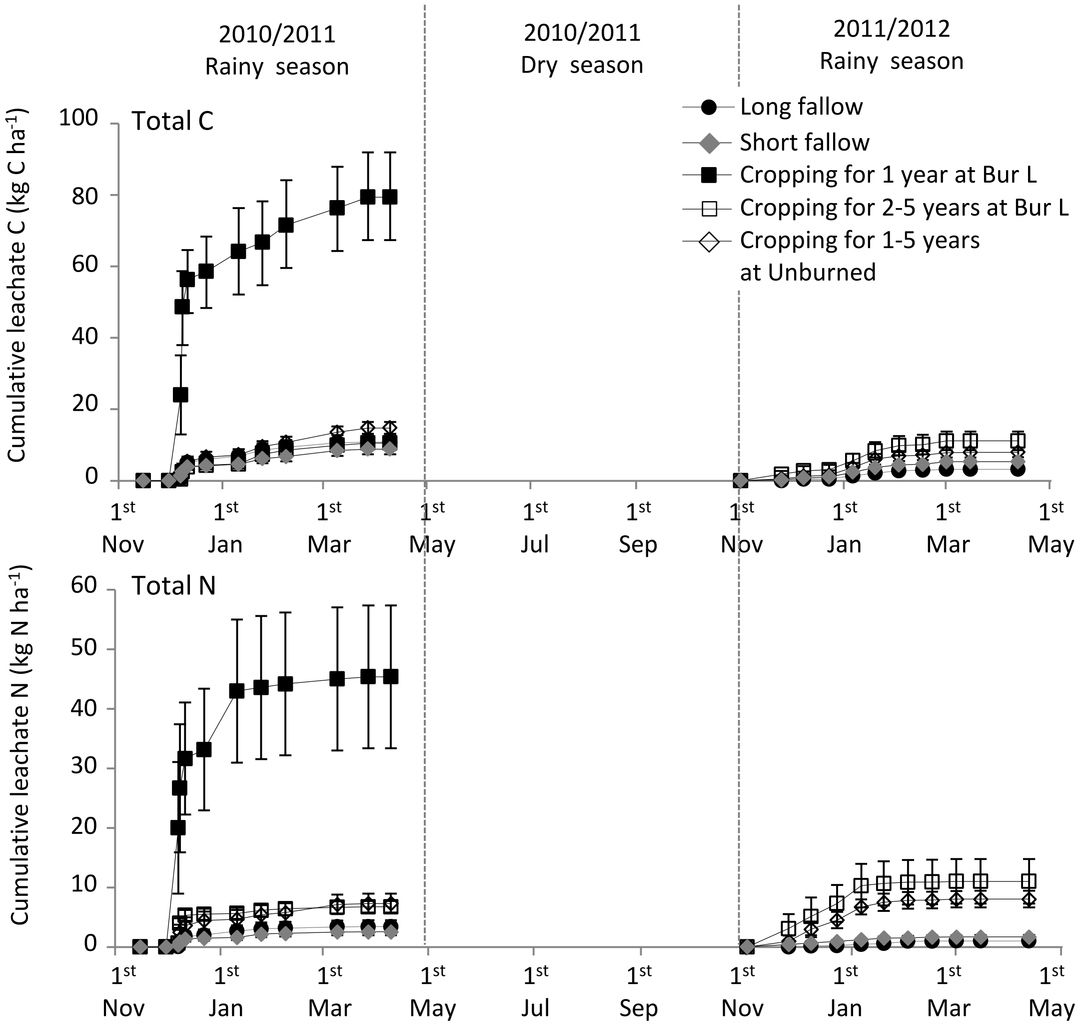


Fig.5.9
Annual cumulative total N and C amounts in leachate during cropping in Unburned and Bur L and fallow in Unburned. Bars indicate standard error (*n*=3).

5.3.5. Budgets of C and N during cropping and fallow

The annual C budget was estimated by the input (plant materials and rainfall) and output (decomposition of organic matter and leaching) and is shown in Tables 5.1, 5.2 and 5.3 for cropland at Bur L, cropland at Unburned, and fallow at Unburned, respectively. The annual change of soil C or N stock (SC or SN) was calculated by subtracting SC or SN in the previous year from that in the respective year.

The annual C amount of leachate and rainfall had small contribution to annual C budget compared with the other flows of input and output in all the treatments (Tables 5.1, 5.2 and 5.3). The annual decomposition of organic matter estimated from CO_2 efflux in all the treatments seemed to be higher in 2010/2011 than that in 2011/2012. Annual decomposition during cropping at Bur L was about 3 Mg C ha^{-1}

year^{-1}, while the input decreased from 5.5 to 2.3 Mg C ha^{-1} year^{-1} as the cropping period increased from 1 year to 5 years (Table 5.1). And then annual C budget was positive in 1- and 2-year cropping (Table 5.1). On the other hand, only in 1-year cropping at Unburned, the input was higher than output and annual C budget was as positive as 2.1 Mg C ha^{-1} year^{-1} (Table 5.2). Then, the decomposition and input of plant materials decreased as cropping period increased and the budget was negative (Table 5.2). After returned to fallow at Unburned, annual decomposition became lower than that in cropland, and decreased from 2.8 to 1.9 Mg C ha^{-1} with increase in fallow periods (Table 5.3). The input of plant material was also lower in 1-year fallow than in cropping and the input decreased with increase in fallow period (Table 5.3). The decomposition was not different significantly among the fallow after the different cropping period (Table 5.3), while the input of plant materials was highest in 2-year fallow after 3-year cropping (3C2F). Reflecting large amount of input, the annual C budget was positive only in 3C2F (Table 5.3).

The annual N budget during cropping was estimated from input to soil (rainfall and plant materials) and output from soil (plant uptake and leaching) (Tables 5.4 and 5.5). The annual flow of input and output were relatively as small as about 4–7% of the soil N stock at Unburned (1240 kg N ha^{-1}) and Bur L (930 kg N ha^{-1}). Only in 1-year cropping at Bur L, N loss via grain yield and leaching was 62 and 45 N kg ha^{-1}, respectively, which accounted for 15% of soil N stock, leading to the annual N budget of –121 kg N ha^{-1} year^{-1} (Table 5.5). In the other treatments at Bur L and Unburned (Table 5.4and 5.5), the annual budget indicated no decrease during cropping.

The annual budget of N during fallow at Unburned was estimated from annual input to soil (litter and rainfall) and output from soil (plant increment and leaching) (Table 5.6). During fallow after 1-year cropping, the N budget tended to be negative because N was stored in the woody stem (Table 5.6). The changes of N budget during fallow were small and accounted for about 0–4% of soil N stock (1230 kg N ha^{-1} at the depth of 0–15cm).

Table 5.1
Annual C budget during short cropping at Bur L

	2010/2011				2011/2012			
	1C	2C	3C	4C	2C	3C	4C	5C
Output (Mg C ha^{-1} year^{-1})								
Decomposition	3.3	3.1	3.3	3.1	2.9	2.9	2.9	2.8
Leachate	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Sum	3.3	3.1	3.3	3.1	2.9	2.9	2.9	2.8
Input (Mg C ha^{-1} year^{-1})								
Plant litter or residue	5.5	3.7	2.7	2.4	3.4	2.3	2.3	2.3
Rainfall	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Sum	5.6	3.8	2.8	2.5	3.5	2.4	2.3	2.4
Budget (input-output) (Mg C ha^{-1} year^{-1})	2.3	0.8	-0.4	-0.5	0.6	-0.6	-0.5	-0.4
SC change* (Mg C ha^{-1} year^{-1})	3.1	1.9	0.0	0.6	1.8	-0.3	1.2	-0.5

*Annual SC (soil C stock) change was calculated by subtracting soil C stock in the previous year from that in the respective year. For example, SC change in 1C was the difference between soil C stock in long fallow and that in 1C.

Table 5.2
Annual C budget during short cropping at Unburned

	2010/2011				2011/2012			
	1C	2C	3C	4C	2C	3C	4C	5C
Output (Mg C ha^{-1} year^{-1})								
Decomposition	4.0	3.8	3.4	2.9	3.6	3.2	2.8	2.5
Leachate	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Sum	4.0	3.8	3.4	2.9	3.6	3.2	2.8	2.5
Input (Mg C ha^{-1} year^{-1})								
Plant litter or residue	6.0	2.8	2.8	2.3	2.6	2.2	2.2	2.3
Rainfall	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Sum	6.1	2.9	2.9	2.4	2.7	2.3	2.2	2.4
Budget (input-output) (Mg C ha^{-1} year^{-1})	2.1	-0.8	-0.5	-0.5	-0.9	-0.9	-0.5	-0.1
SC change (Mg C ha^{-1} year^{-1})	0.4	0.3	-0.6	0.2	0.4	-0.7	0.4	0.6

Table 5.3

Annual C budget during short fallow after different cropping period at Unburned

	2010/2011						2011/2012					
	1C1F	1C2F	1C3F	2C1F	2C2F	3C1F	1C2F	1C3F	1C4F	2C2F	2C3F	3C2F
Output (Mg C ha^{-1} year^{-1})												
Decomposition	2.6	2.6	2.4	2.8	2.2	2.7	2.4	1.9	1.9	2.1	2.0	2.2
Leachate	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Sum	2.6	2.6	2.4	2.8	2.2	2.7	2.5	1.9	1.9	2.1	2.0	2.2
Input (Mg C ha^{-1} year^{-1})												
Plant litter or residue	1.9	1.2	1.4	2.1	1.5	2.0	1.6	1.2	1.5	1.8	1.5	2.5
Rainfall	0.2	0.2	0.2	0.2	0.2	0.2	0.1	0.1	0.1	0.1	0.1	0.1
Sum	2.0	1.4	1.6	2.3	1.7	2.2	1.7	1.3	1.6	1.9	1.5	2.6
Budget (input-output) (Mg C ha^{-1} year^{-1})	-0.6	-1.2	-0.8	-0.6	-0.5	-0.6	-0.7	-0.7	-0.3	-0.2	-0.4	0.4
SC change (Mg C ha^{-1} year^{-1})	-0.7	-0.3	-1.6	-0.9	0.0	-1.4	-0.4	-0.8	0.6	-0.0	0.7	1.0

Table 5.4

Annual N budget during short cropping in Bur L

	2010/2011				2011/2012			
	1C	2C	3C	4C	2C	3C	4C	5C
Output (kg N ha^{-1} year^{-1})								
Harvested grain	62	24	19	11	31	23	29	19
Maize stover and weed	34	29	26	23	26	23	21	18
Leachate	45	8	8	5	21	12	6	5
Sum	142	60	52	39	79	59	56	42
Input (kg N ha^{-1} year^{-1})								
Ash or plant residue	9	34	29	26	34	26	23	21
Rainfall	12	12	12	12	10	10	10	10
Sum	21	46	41	38	44	37	34	31
Budget (input-output) (kg N ha^{-1} year^{-1})	-121	-14	-12	-2	-34	-22	-22	-11
SN change* (kg N ha^{-1} year^{-1})	-55	2	9	-8	-11	20	31	-23

*Annual SN (soil N stock) change was calculated by subtracting soil N stock in the previous year from that in the respective year. For example, SN change in 1C was the difference between soil N stock in long fallow and that in 1C.

Table 5.5

Annual N budget during short cropping at Unburned

	2010/2011				2011/2012			
	1C	2C	3C	4C	2C	3C	4C	5C
Output (kg N ha^{-1} year^{-1})								
Harvested grain	12	10	12	13	14	13	11	14
Maize stover and weed	43	36	29	27	40	31	29	27
Leachate	7	3	9	11	12	6	6	7
Sum	62	48	50	50	65	50	46	48
Input (kg N ha^{-1} year^{-1})								
Plant residue	81	40	32	29	43	36	29	27
Rainfall	12	12	12	12	10	10	10	10
Sum	93	52	44	41	54	46	39	37
Budget (input-output) (kg N ha^{-1} year^{-1})	30	4	-6	-9	-12	-4	-7	-11
SN change (kg N ha^{-1} year^{-1})	20	-29	3	39	-39	-4	-31	6

Table 5.6

Annual N budget during short fallow after different cropping period at Unburned

	2010/2011						2011/2012					
	1C1F	1C2F	1C3F	2C1F	2C2F	3C1F	1C2F	1C3F	1C4F	2C2F	2C3F	3C2F
Output (kg N ha^{-1} year^{-1})												
Plant increment	17	32	51	19	24	29	42	44	80	26	38	26
Leachate	4	3	4	1	1	2	1	1	3	1	1	2
Sum	21	35	55	20	25	32	44	45	84	27	39	28
Input (kg N ha^{-1} year^{-1})												
Litter	15	26	32	17	25	18	26	32	43	25	28	36
Rainfall	12	12	12	12	12	12	10	10	10	10	10	10
Sum	27	38	44	29	37	30	36	42	54	35	38	46
Budget (input-output) (kg N ha^{-1} year^{-1})	6	3	-11	9	12	-2	-7	-3	-30	8	-1	18
SN change (kg N ha^{-1} year^{-1})	-40	-3	-46	-13	-22	-31	-47	5	-36	-54	4	51

5.4. Discussion

5.4.1. Effect of land use change on volume of drainage

The annual volume of drainage in this study (Fig. 5.7) was comparable to the measurement in Zimbabwe with similar climatic condition and soil texture. The drainage of 80–300 mm was reported in Mapanda et al. (2012). The highest volume of drainage in 1-year cropping at Bur L (Fig. 5.7) was partly derived from the high infiltration rate after burning (Fig. 5.3). Additionally, the fluctuation of soil volumetric water content in 1-year cropping at Bur L suggested rapid desiccation of surface soil (Fig. 5.4). Those results indicated that the rainfall at Bur L was infiltrated rapidly and drained. Moody et al. (2009) also reported high infiltration rate in burned places. The lower volume of drainage in the fallow than in cropland (Fig. 5.7) was partly caused by the woody biomass which could uptake more water (Fujii et al., 2013).

5.4.2. Soil carbon budget

Flows of C via rainfall and leaching had little contribution to the C budget in all the treatments because of the low concentration of total C (Tables 5.1, 5.2 and 5.3). The amount of leachate C in 1-year cropping at Bur L was highest because of partly transformation of soil organic matter into dissolved organic matter by burning, but still had low contribution to the budget (Table 5.1). The small C amounts in annual rainfall and leachate was reported even in humid tropics in Thailand where rainfall was 2000 mm (Fujii et al., 2013), and also those flow had little effect on C budget. The amount of root input as plant materials in fallow might be overestimated because the turnover of woody fine root was not estimated in the experiment (Gill and Jackson, 2000; Graefe et al., 2008). However, because the amount of root was about 0.4 Mg ha^{-1} accounting only for 10% of total input, the probable overestimation would have small contribution to the whole budgets.

The annual CO_2 efflux was main output flow as a result of decomposition of organic matter and estimated by soil moisture. The strong correlation between CO_2 efflux rate and soil moisture (Fig. 5.6) was also observed in regions with similar climatic conditions (Mapanda et al., 2010; Merbold et al., 2011; Rey et al., 2011; Sugihara et al., 2012). Therefore, the decomposition was constrained during 6 months of dry season, which brought small decrease in soil C stock during cropping and fallow. The annual decomposition in all the treatments seemed to be higher in 2010/2011 than that in

2011/2012 (Table 5.1, 5.2 and 5.3). These differences were derived from higher annual rainfall in 2010/2011 (1081 mm) than in 2011/2012 (879 mm), leading to slightly higher average soil volumetric water content in 2010/2011 (Fig. 5.5) than in 2011/2012 (Fig. 4.2 in Chapter 4).

In 1-year cropping at Bur L, the highest CO_2 flux rate in the first week of December (Fig. 5.5) reflected the large amount of highly mineralizable C in soil by burning (Fig. 3.3 in Chapter 3). Then, the efflux seemed to become lower partly due to slowly decomposable input of ash (Andersson et al., 2004; González-Pérezet al., 2004; Kendawang et al., 2005 Castaldi et al., 2010). Therefore, the coefficient of determination of the efflux estimation in 1-year cropping at Bur L ($r^2 = 0.8$) could be improved by adding substrate as an explanatory variable. The C budget estimated by annual output and input in 1-year cropping at Bur L was almost same as the SC change measured by soil (Table 5.1), considering the standard error of SC (1.0 Mg C ha^{-1}). Annual decomposition did not change during cropping although the large amount of input in 1- and 2-year cropping decreased with cropping (Table 5.1). It reflected the slowly decomposable input of ash in 1-year cropping (Table 5.1) and maize stem in 2-year cropping which became hard stem with increase in the biomass to sustain standing. Therefore, the large amount of input composed of slowly decomposable plant materials of 1- and 2-year cropping could bring the increase in soil C stock at Bur L (Fig. 5.2). After 3-year cropping, the decomposition as same as the input because the input was composed of decomposable plant materials such as maize with small biomass and herbaceous weeds and then were decomposed easier than ash and maize with large biomass (Table 5.1).

During cropping at Unburned, the annual decomposition decreased from 1-year to 5-year cropping (Table 5.2), depending on the changes of input (Adiku et al., 2008; Sugihara et al., 2012). The C budget was as positive as 2.1 Mg C ha^{-1} in 1-year cropping (Table 5.2), reflecting large amount of slowly decomposable input composed of woody litter (Table 4.1 in Chapter 4). Singh et al. (2009) also reported that C budget was as positive as 1.6 Mg C ha^{-1} with slowly decomposable input of 5.6 Mg C ha^{-1} in semiarid tropical cropland. This remaining organic matter of 2.1 Mg C ha^{-1} could compensate the negative annual C budget during 2- to 4-year cropping. Thus, the total amount of C input through the cropping for 4 years compensated the total C output, and then soil C stock did not decrease and only the labile fraction decreased during cropping for 4 years.

After returned to fallow at Unburned, the decomposition of organic matter became lower than in cropland due to decrease in the input (Table 5.3), and plant materials left on surface (Huggins et al., 1996; Laudicina et al., 2014). Therefore, soil C stock was not restored during short fallow for 1 to 4 years because the input of plant materials could not exceed the decomposition of organic matter, which was also reported during short fallow in tropical dry region (Aweto, 1981), and tropical humid region (Szott et al., 1999). However, input in 3C2F was larger than the decomposition of organic matter (Table 5.3) derived from high herbaceous litter productivity due to low woody biomass, and then annual C budget was positive.

5.4.3. Soil nitrogen budget

In 1-year cropping at Bur L, release of NH_4–N from soil organic matter by burning (Table 3.5 in Chapter 3) caused the high concentration of NH_4–N in leachate (Fig. 5.8). The following high concentration of NO_3–N (35 mg L^{-1}) in leachate (Fig. 5.8) was observed after recovery of nitrifying bacteria killed by burning (Johnson et al., 2011), which was even higher than that of 25 mg L^{-1} with 120 kg N ha^{-1} of fertilizer reported in Zimbabwe (Mapanda et al., 2012).

Except for 1-year cropping at Bur L, the relatively high concentration of NO_3–N in leachate at the beginning of rainy season was derived from rapid decomposition of soil organic matter at the onset of rains after a pronounced dry season during cropping and fallow (Chikowo et al., 2004). The higher NO_3–N concentration in leachate during cropping (Fig. 5.8) than in fallow was attributable to soil organic matter decomposition or low crop uptake by plants at early stage of rainy season because of small maize biomass, and those results were consistent with the previous reports (Chikowo et al., 2004; Funakawa et al., 2006; Fujii et al., 2013). The low concentration of NO_3–N in leachate in 1-year cropping at Unburned (Fig. 5.8) could be explained by the findings in N mineralization experiment, where only 30 kg N ha^{-1} was mineralized for 4weeks in 1-year cropping, while 50 kg N ha^{-1} in 2-year cropping (Fig. 3.3 in Chapter 3 and Appendix I). After returned to fallow at Unburned, the concentration of NO_3–N in leachate became low with increase in fallow period (Fig. 5.8) because NO_3–N could be caught by well-developing woody root compared to cropland (Chikowo et al., 2004).

The changes of concentration of NO_3–N in leachate by land use did not affect largely on soil N stock because the annual N loss via leaching accounted only for 0.2 to 0.9% of the N stock (Figs. 5.2 and 5.9). However, in 1-year cropping at Bur L, the annual N loss via leaching was highest and had negative effect of N budget (Table 5.2), which was also reported under slash-and-burn agriculture in Amazon (Sommer et al., 2004). During short cropping at Bur L and Unburned except for 1-year cropping at Bur L, annual loss via leaching and harvesting was small (Tables 5.4 and 5.5). Those were comparable to those measurements in semiarid tropical dryland agriculture, where 4–10 kg N ha^{-1} year^{-1} of the leachate (Nyamangara et al., 2003; Mapanda et al., 2012) and 14–18 and 20–35 kg N ha^{-1} year^{-1} of the grain and plant uptake (Mtambanengwe and Mapfumo, 2006) were observed. Therefore, the even small input N via rainfall (10 kg N ha^{-1} year^{-1}) could largely affect the N budget (Tables 5.4, 5.5, and 5.6), and the soil N stock did not change.

After return to fallow at Unburned, soil N stock did not change because of small loss via leaching and woody increment (Table 5.6). The budget tended to be negative with increase in fallow period because large amount of absorbed N by woody plants was stored in stem than in litter (Fujii et al., 2013). With longer fallow period, N budget could be positive with increase in litter fall (Szott et al., 1999; Hartemink et al., 2000). Those small decreases in soil N stock might be compensated by free living N$_2$ fixation about 3–30 kg N ha^{-1} reported in tropical savanna (Reed et al., 2011).

5.4.4. Net C and N budgets after cropping and short fallow rotation

Cumulative C and N budget in combination of different cropping and short-fallow periods at Unburned were shown in Fig. 5.10. Total loss of C during cropping for 3 years could be roughly balanced with input of plant materials. Even after returned to fallow, the C budget was as negative as that in cropland. On the other hand,

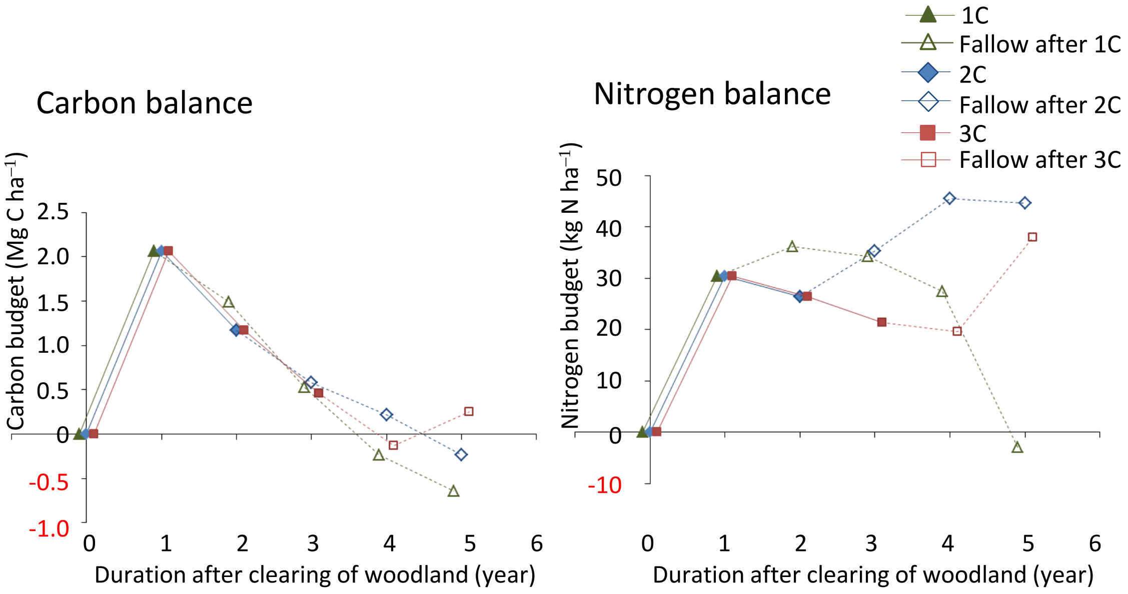


Fig.5.10
Cumulative C and N balance in combination of different cropping and short-fallow periods

the changes of N budget was relatively small during cropping for 1, 2 and 3 years and fallow for 1 and 2 years after any cropping period, while N budget tended to be negative in 4-year fallow after 1-year cropping where the woody biomass increased. In fallow, the C and N were stored in woody biomass. At the time of clearing, only 5% of C and 1% of N stored in woody biomass would be returned as ash, because the woody biomass is burned at clearing for cropland. Therefore, in case of clearing long fallow, the rotation of 3-year cropping before 2-year fallow was more useful. This rotation will allow high ratio of cropping to fallow period and keep soil C and N stock (Fig. 5.10).

5.5. Conclusion

Soil C and N stock decreased by burning could not be fully restored during short fallow, although the soil C stock was restored gradually in 1- and 2-year cropping. After burned, annual decomposition of organic matter in 1- and 2-year cropping was lower than input returned to soil due to the input composed of slowly decomposable plant materials. Nevertheless, soil N stock decreased by 56 kg ha^{-1} after 1-year cropping because the annual loss was high due to large loss of N via leaching and production. N loss, especially by burning, was not recovered during short fallow because of low N input to soil. On the other hand, soil C and N stocks at unburned spots during cropping and fallow did not decrease apparently. No decrease in soil C stock during cropping for 4 years was attributed to larger total C input than the annual decomposition of organic matter because of the large amount of slowly decomposable input in 1-year cropping. After returned to fallow at unburned spots, annual decomposition of organic matter were balanced with the input. Only in 2-year fallow after 3-year cropping, input was larger than the annual decomposition of organic matter. Because of the low N loss via harvesting, woody increment and leaching during cropping and fallow, the even small input N via rainfall and litter could affect N budget and then the changes of soil N stock was negligible. However, N budget became negative with fallow for more than 4 years due to high N loss via woody increment. Then, in case of the cropping after clearing long fallow, 3-year cropping and 2-year fallow was relatively useful rotation at unburned spots. With return of plant residue, the decrease in soil C and N stock during cropping was small. The C and N stock could not be fully recovered, especially burned spots, but was not lost drastically by the cropping and short fallow rotation in the region at both of burned and unburned spots.

Chapter 6

Summary and conclusion

6.1. Immediate effects of slash-and-burn on soil organic matter and vegetation

In Eastern Province, Zambia, the spots unburned and burned with emergent and bush tree piles could be present simultaneously within the cleared field after burning. The different extent of burned biomass (emergent and bush tree piles) brought the different fire intensity which affected soil organic matter (SOM) degradation and nutrient release. The fire intensity was significantly higher at spots burned with emergent tree piles in terms of maximum temperature and duration of burning. With increase in fire intensity, SOM was degraded by soil heating and C and N contents of SOM decreased. Especially labile fraction of SOM such as coarse organic matter (COM; > 2000 μm) and particulate organic matter (POM; 53–2000 μm), composed of plant detritus in various stages of decomposition, was degraded by burning. The degradation of SOM and microbial mortality brought the increase in available nutrients such as NH_4–N, available P, and exchangeable K and Ca with an increase in fire intensity. As a result, maize grain yield increased with fire intensity, which was also attributed to limited weed biomass by soil heating. Thus, the recent decrease in emergent trees brought high spatial variability of fire intensity inside the cleared field, which caused high spatial variability of the amount of SOM, especially for labile SOM fraction and available nutrients. Because more areas are being burned with bush trees owing to the decrease in emergent trees, grain yield may decrease, although the severe decrease in SOM may be alleviated.

6.2. Effects of cropping and short fallow rotation on soil organic matter

At each spot unburned, burned with emergent trees, and burned with bush trees, the changes of SOM during cropping were different. After returned to fallow, the restoration process of SOM was affected by not only the fire intensity but also cropping period before returned to fallow through the changes of amount and composition of input.

Changes of C contents of soil organic matter through input

The major flow of C loss was CO_2 efflux as a result of decomposition of SOM which was restricted by soil moisture and the amount and composition of input. In the semiarid tropics of Zambia, long dry season for 6 months constrained the rapid decomposition of SOM during cropping. The changes of quantity of input were partly due to the different amount of available nutrients by burning and cropping, while composition of input changed by burning and cropping. For instance, decrease in trees coppicing ability by increase in cropping period and fire intensity, which brought decrease in the proportion of woody weed or litter in input.

Large amount of input in 1-year cropping at the unburned spots could compensate the negative soil C budget during cropping for 2 to 4 years partly and then drastic decrease in soil C stock was found only after long cropping. However, the gradual decrease in woody weed during short cropping, which was decomposed more slowly than herbaceous weeds, brought the gradual decrease in C contents in POM. In spots burned with emergent trees and bush trees, soil C stock and labile fraction C decreased by burning could be restored by the large amount of input of ash, hard stem of maize to sustain large maize stover which was decomposed slowly.

After returned to fallow at unburned spots, the gradual decrease in C contents in POM during cropping was restored during 2-year fallow after 3-year cropping with relatively large input. It was attributed to the large input from the accelerated growth of herbaceous plants due to the decreased competition with woody biomass which decreased with the increase in previous cropping period. On the other hand, soil C stock including COM and POM did not recover at spots burned with both of emergent trees and bush trees.

Changes of N contents of soil organic matter through input

Soil N stock decreased during burning via volatilization of N, during cropping via high leachate and high production in 1-year cropping at spots burned with emergent trees, and during cropping for more than 10 years via continuous grain harvesting. The small N loss from soil during short cropping at unburned and burned spots (except for 1-year cropping) was attributed to low leachate and low grain yield with restricted mineralization of SOM to inorganic N during dry season. Then, the even small input N via rainfall could largely affect the N balance. Therefore, soil N stock did not decrease during short cropping at spots unburned with and burned with emergent and bush tree piles.

Decrease in N contents of POM by burning was restored gradually during cropping. The redistribution of N from mineral-associated organic matter to COM and/or POM through the input of plant materials in Bur L was enhanced by degradation or disruption of mineral-associated organic matter by intensive burning. The N contents of degraded mineral-associated organic matter might be absorbed more easily by plant.

After returned to fallow for 1 to 3 years, soil N stock decreased by burning was not restored. Short fallow was not adequate period for the restoration of soil N stock because of the low woody biomass which could not redistribute N from deep horizon to surface soil via litter deposition.

6.3. Evaluation of cropping and short fallow rotation under slash-and-burn agriculture in a semiarid woodland

The results of cropping and short fallow rotation are shown in Fig. 6.1. More than 10-year cropping exhausted SOM and woody biomass, SOM and woody biomass were not restored during short fallow. At spots burned with emergent and bush trees, SOM decreased only by burning and could be restored during short cropping, although N contents of SOM and woody biomass were not restored even during fallow. Without burning, 2-year fallow after 3-year cropping is relatively useful management in terms of maintenance of POM, SOM and grain yield, although woody biomass decreased compared to 2-year fallow after 1-year cropping. The C and N stock could not be fully recovered, especially burned spots.

Under rainfed agriculture without fertilizer in semiarid region, this type of slash-and-burn was relatively suitable to maintain grain yield and SOM contents although the yield and the SOM was low level compared to other region where slash-and-burn is practiced. In other region such as Central Africa, Southeast Asia and South America, soil C and N stock decreased rapidly even during short cropping, while grain yield was higher than this semiarid region (Kauffman et al., 1995; Kendawang et al., 2004; Tanaka et al., 2004; Funakawa et al., 2006; Okore et al, 2007). However, in the semiarid region, the decrease in soil C and N stock during cropping was small with return of plant residue because long dry season constrain loss of SOM through leaching and decomposition and N_2 fixation by free-living N_2 fixation. Therefore, SOM will not decrease drastically under short cropping and short fallow rotation because recent decrease in emergent trees and increase in bush trees brought small loss of SOM during burning.

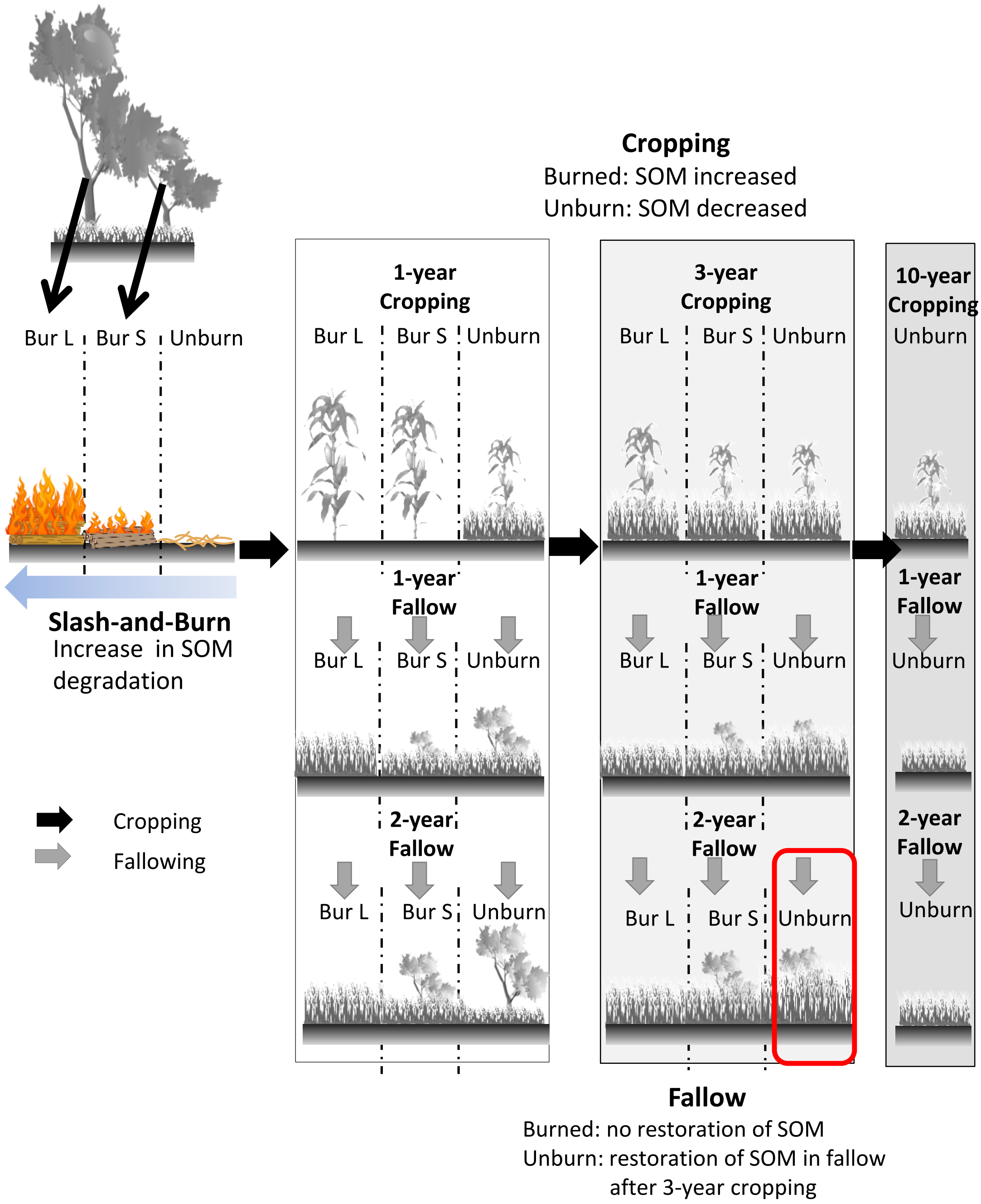


Fig. 6.1
Changes of soil organic matter through vegetation during cropping and fallow duration.

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Appendix I

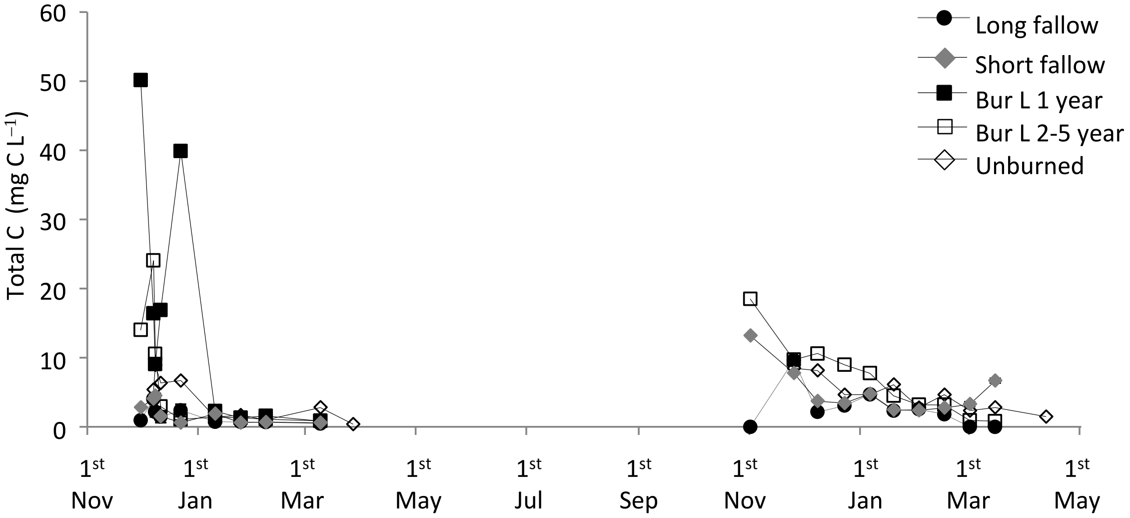

Fig.A.1

The concentrations of total C in leachate during cropping in Unburned and Bur L and during fallow in Unburned in rainy season of 2010/2011 and 2011/2012. Bars indicate standard error (*n*=3).

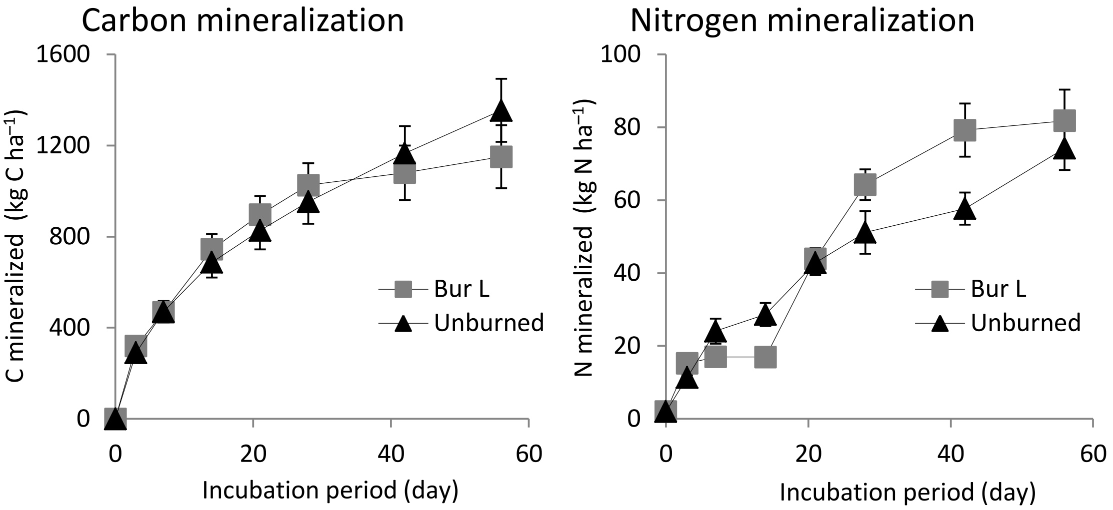

Fig.A.2

Cumulative C mineralization and N mineralization at a depth of 0–15 cm during the incubation experiment in 2-year cropping. Bars indicate standard error (*n* = 3).

Appendix Π

Japanese abstract (概要)

ザンビア半乾燥疎開林の焼畑における土壌有機物動態に関する研究

第1章　序論

半乾燥熱帯地域に位置するザンビアでは、土壌有機物は作物にとって重要な養分の給源である。当地域では伝統的に、耕作で減少した土壌有機物を長期休閑によって回復し、持続的な土地利用を行ってきた。しかし近年、土地利用圧の増加にともなって休閑年数は短期化しており、土壌有機物の動態も変化すると考えられるが、未だ明らかではない。熱帯湿潤地で行われる一般的な火入れでは、バイオマス量が150–350 Mg ha^{-1}と多く、開墾地全体に樹木を積み上げ燃やす。一方で当地域では低木と高木から成るバイオマス量が69 Mg ha^{-1}と少ない疎開林が広がり、開墾の際に開墾地全面積に樹木を積み上げ燃やすことが難しく、一部にのみ樹木を積み上げて火を入れる。また休閑の短期化にともなって高木は減少し、開墾地内に低木のみが積み上げられた場所も存在している。よって開墾地内には高木と低木を燃やした場所、火が入らなかった場所が存在し、開墾地内は火入れ強度の空間的なばらつきが大きくなっている。火入れ強度の違いは土壌温度上昇の程度を変化させるので、土壌有機物が燃焼し減少する量、土壌有機物の分解と微生物の死滅にともなって放出される養分量、雑草種子の死滅やひこばえの再生能力の低下の程度も異なると考えられる。これらの違いを反映し、耕作中の土壌有機物の減少の過程も変化すると考えられる。休閑期間の短期化および圃場内での火入れ強度のばらつきが大きくなっている状況下において、耕作中に減少した土壌有機物を短期の休閑で回復できるのかを解明することが求められている。

そこで、火入れ強度の違いと短期休閑が土壌有機物量に与える影響を解明するため、以下の研究を実施した。第2章ではザンビアの気候と試験区の設定について記し、第3章では火入れ強度が火入れ直後の土壌有機物量の変化に与える影響を解明し、第4章・第5章では火入れ強度の違う場所ごとに、①1－40年の異なる耕作年数が土壌有機物の減少量に与える影響と、②各耕作年数後、短期の休閑に戻すと土壌有機物はどのように回復するのかを解明することを目的とした。第4章では土壌へ投入される有機物の量と有機物の種類の変化と、土地利用の影響を受けやすい易分解性の土壌有機物画分の変化に着目し、第5章では土壌への投入量と土壌からの損失量を求め物質収支によって土壌有機物量を評価した。

第2章　研究対象地の概要と試験設定

調査地はザンビア共和国東部州の疎開林に設置した（バイオマス量：39 Mg ha^{-1}）。ザンビアは明瞭な雨季（11月‐4月）と乾季（5月‐10月）があり、年平均降水量は855 mmで、年平均気温は24℃である。土壌はTypic Plinthustalfs（Soil Taxonomy）に分類された。2007-2010年の10月に、毎年新たな圃場を開墾し、火入れをおこなった。開墾した圃場は毎年その一部を休閑に戻した。これによって耕作年数1－5年の5処理区、1年の耕作後に1－4年休閑した4処理区、2年の耕作後に1－3年休閑した3処理区、3年の耕作後に1、2年休閑した2処理区の計14処理区を設定した。各処理区三連ずつとした。火が入った場所は各圃場にパッチ状に広がり、燃やしたバイオマス量は80 Mg ha^{-1}（低木）、200 Mg ha^{-1}（高木）となった。また長期耕作圃場として10、40年間耕作をおこなっている圃場を1、2年休閑にもどす処理区も設定した（火が入らなかった耕地のみ）。

第3章　火入れ強度の違いが土壌有機物量および養分の可給化に及ぼす影響

ザンビア東部州の焼畑によって開墾地内に存在する火が入らなかった場所、高木と低木を燃やした場所それぞれにおいて火入れ直後の土壌有機物量と植物が利用しやすい可給態養分量を評価した。火入れ強度の増加とともに土壌有機物の燃焼と分解が促進され、土壌炭素量は高木を燃やした場所で25.1%、低木を燃やした場所で14.7%減少した。土壌窒素量はとくに高木を燃やした場所で15.0%減少したので、易分解性有機物中の窒素量も一部減少した結果、正味の窒素無機化は進行しなかったと考えられる。しかしこの土壌有機物の燃焼・分解と、微生物の死滅によって、アンモニア態窒素・可給態リン・交換性カリウム・交換性カルシウムといった植物が利用しやすい養分量は増加した。火入れ強度とともに増加した養分量と雑草の抑制により、トウモロコシ収量も増加した。その結果、高木・低木を燃やした場所はそれぞれ全耕地面積の6.9%・7.5%を占めるにすぎないが、それぞれは全耕地の21%・15%の収量を占めた。以上の結果から、高木の減少によって低木のみを燃やす場所が増加すると、耕地全体の収量は減少するが、同時に火入れによる土壌有機物の急激な減少は緩和されることがわかった

第4章　耕作－休閑サイクルが土壌有機物および植生に与える影響

火入れ強度の違いが、耕作による土壌有機物の減少に影響を与えるのか、そしてそれぞれを休閑に戻した後、減少した土壌有機物は回復するのかを解明することを目的とした。まず土壌へ投入される有機物の量と有機物の種類を通して土壌有機物量はどのように変化するのか、特に土地利用の変化を受けやすい易分解性の有機物量に着目し評価を行った。

【火が入らなかった場所】

短期耕作では土壌炭素量と窒素量は減少しなかった。しかし、易分解性有機物であるCOM（粗大有機物; 2000 µm以上）とPOM（particulate organic matter; 53–2000 µm）

に含まれる炭素量は変化し（窒素量は変化なし）、土壌への有機物の投入量と、微生物による分解をうけにくい木本雑草の投入量の減少とともに徐々に減少する傾向を示した。休閑に戻すと、減少したPOM中の炭素量は草本バイオマスが優占した耕作3年後の休閑でのみ回復した。樹木が優占した休閑では、土壌へ投入される有機物量は樹木の落葉落枝のみで、むしろ耕地よりも投入量は少なくなった。しかし、耕作3年間で樹木の再生能力が低下し休閑中に草本が優占した結果、土壌への有機物投入量が増加したことが、減少した易分解性有機物の炭素量の回復をもたらしたと考えられる。長期耕作によって減少した土壌有機物中の炭素量は回復傾向を示したが、窒素量は回復せず、10年以上の長期耕作を行ってしまうと、土壌有機物量は短期の休閑で充分に回復できないことがわかった。

【火が入った場所】

高木を燃やした場所では、火入れによって減少した土壌有機物・易分解性有機物中の炭素量は耕作1・2年目に、燃やす前の量の8割程度まで増加した。火入れの際に生成した灰と1年目に生産されたトウモロコシ茎葉量が非常に多かったので、増加したと考えられる。低木を燃やした場所では易分解性有機物中の炭素量のみ減少したが、1年目のトウモロコシ茎葉量が多かったので、燃やす前の9割程度まで炭素量は増加した。しかし休閑に戻すと、火入れ強度に関係なく土壌有機物・易分解性の有機物中の炭素量は増加しなかった。火入れによって減少した土壌窒素量は耕作中に大きな減少こそしなかったが、休閑に戻しても火入れ強度に関係なく回復しなかった。火入れ強度の増加にともなって木本バイオマスの再生速度は遅くなったので、リターを通して下層から表層への窒素の再分配がほとんどなかったと考えられる。とくに高木を燃やした場所では、火入れによって難分解性画分の窒素が分解し、作物に吸収されることで易分解性有機物中の窒素量に再分配され、増加した。

以上の結果をまとめると、火が入らない場所では、耕作3年間後に2年間休閑をすれば、木本バイオマス量の回復は遅くなるものの、減少したPOM中の炭素量は回復できると考えられた。また火入れによって減少した土壌有機物量は耕作中に回復し、休閑中には変化しなかった。

第5章　短期耕作－短期休閑サイクルでの炭素・窒素収支の解明

土壌炭素量と土壌窒素量は、土壌への炭素・窒素の投入と、土壌からの損失によって変化する。それぞれの経路におけるフラックスを測定し、土壌の炭素と土壌窒素の収支を算出した。土壌炭素の主要な損失経路であるCO_2放出量（有機物分解量）は土壌体積含水量に依存して変動したので、年間の有機物分解量を土壌体積含水量から推定した。高木を燃やした場所では、土壌へ投入される有機物量は耕作年数の増加と伴に減少したが、有機物分解量は変化しなかった。耕作1・2年目は分解されにくい灰や、トウモロコシの太い茎などで構成される有機物が多量に土壌へ投入された結果、投入量が分解量を上回り、土壌炭素量は増加した。耕作3年目以降は草本雑草など比較的分解されやすいもので構成された有機物が土壌へ投入され、投入量と分解量が一致し、土壌炭素量は変化しなかったと考え

られる。火が入らなかった場所の有機物分解量は、土壌への有機物投入量に依存して変化し、耕作年数の増加とともに減少した。耕作 1 年目に土壌へ大量に投入された有機物のうち 2.1 Mg C ha^{-1}は分解されずに残り、その後 3 年間に分解された結果、耕作 4 年間の炭素収支はマイナスにならず、土壌炭素量も変化しなかったと考えられる。火が入らなかった場所では休閑に戻すと、土壌へ投入される有機物量が減少し、有機物分解量も減少したが耕作 3 年後の休閑 2 年目のみ、土壌への有機物投入量が分解量を上回り、炭素収支はプラスとなった結果、耕作中に減少した POM 中の炭素量が回復したと考えられる。

土壌からの窒素の損失となるトウモロコシ収量 1 Mg ha^{-1}（12 kg N ha^{-1}）、溶脱量（3–11 kg N ha^{-1}）は、土壌窒素量（1230 kg N ha^{-1}）に比べてかなり小さく、降水による窒素の投入（10 kg N ha^{-1}）も窒素収支にプラスの影響を与えた。その結果、火入れの有無に関わらず、窒素の収支はマイナスを示すものの、短期の耕作では土壌窒素は減少しなかった。ただし、火入れ直後 1 年目の耕作では、収量も溶脱量も高かったので、土壌窒素量は 121 kg N ha^{-1}減少した。

耕作・休閑中の炭素・窒素収支から、長期休閑地を開墾した場合では、少なくとも 3 年間の耕作であれば 2 年間の休閑によって十分回復できることがわかった。当地域では半年に及ぶ長い乾季があることで、土壌有機物の分解が抑制され、また溶脱量も少なくなり、土壌炭素量・窒素量の著しい減少は起こらなかったと考えられる。

第 6 章　要約と結論

ザンビア東部州では、昨今の休閑の短期化によって開墾地内に生じた 3 つの火入れ強度（高木を燃やした場所・低木を燃やした場所・火入れなし）によって、土壌有機物の①耕作による減少過程、②休閑による回復過程、は異なった。火が入らなかった場所では、短期の休閑で減少するのは易分解性の土壌有機物画分のみであり、耕作 3 年後に休閑を 2 年間すれば回復した。短期の休閑で回復を行う場合、耕作年数を 3 年以上とし、ある程度木本が減少し、草本が優占した状態で休閑した方が、土壌中の炭素量は蓄積する可能性が示唆された。一方で火が入った場所では耕作中に火入れによって減少した土壌炭素量は高木を燃やした場所で 8 割近く、低木を燃やした場所で 9 割近くまで回復し、休閑では変化しなかった。当地域では、土壌へ投入される有機物量や有機物の種類によって土壌有機物量は変化しており、残渣やリターを土壌へ還元すれば、耕作中に土壌有機物は過度に減少しないことが明らかとなった。よって、当地域は焼畑農業を行っている他地域より、耕作による土壌有機物の減少は小さく、短期休閑でも十分に土壌有機物を回復できる可能性が高いと考えられる。

Publications

Chapter 3

Ando, K., Shinjo, H., Noro, Y., Takenaka, S., Miura R., Sokotela, S.B., Funakawa, S., Short term effects of fire intensity on soil organic matter and nutrient release after slash-and-burn in Eastern Province, Zambia. Soil Science and Plant Nutrition, article in press.

Chapter 4

Ando, K, Shinjo, H., Kuramitsu, H., Miura R., Sokotela, S.B., Funakawa, S., Effects of cropping and short-natural fallow rotation on soil organic carbon in the Eastern Province of Zambia. Agriculture, Ecosystems and Environment (Under review)

Chapter 5

Ando, K, Shinjo, H., Kuramitsu, H., Miura R., Sokotela, S.B., Funakawa, S., Soil carbon and nitrogen budgets in cropland and fallow under slash-and-burn agriculture in the Eastern Province of Zambia. Agriculture, Ecosystems and Environment (Under review)