CSIRO PUBLISHING

International Journal of Wildland Fire
http://dx.doi.org/10.1071/WF16022

Research Note

The impact of traditional fire management on soil carbon and nitrogen pools in a montane forest, southern Ethiopia

Dong-Gill Kim[A,C], *Habitamu Taddese*[A], *Abrham Belay*[A] and *Randy Kolka*[B]

[A]Wondo Genet College of Forestry and Natural Resources, Hawassa University, PO Box 128, Shashemene, Ethiopia.
[B]USDA Forest Service, Northern Research Station, 1831 US Highway 169 East, Grand Rapids, MN 55744, USA.
[C]Corresponding author. Email: donggillkim@gmail.com

Abstract. We conducted studies to assess the impact of traditional fire management on soil organic carbon and total nitrogen pools. We compared organic carbon and total nitrogen pools in forest floor and mineral soil (0–100-cm depth) in three areas burned by local communities (B) with adjacent unburned areas (UB) (three paired sites; 1, 5 and 9 years since fire; hereafter B1-UB, B5-UB and B9-UB) in a montane forest in southern Ethiopia. Despite differences in time since fire and dominant post-fire vegetation, forest floor and mineral soil organic carbon and total nitrogen concentrations and pools were not significantly different between burned and unburned pairs or across sites. However, mineral soil carbon : nitrogen ratio was significantly higher in the burned area of B9-UB (0–10 cm) and B5-UB (10–20 cm), indicating small losses of nitrogen relative to carbon, likely from plant uptake or possibly leaching of nitrogen post fire. Combined, the data suggest that traditional fire management did not dramatically affect forest floor and mineral soil organic carbon and total nitrogen dynamics at these sites.

Additional keywords: C : N ratio, forest floor, mineral soil layers, Wondo Genet Forest.

Received 25 January 2015, accepted 30 June 2016, published online 21 July 2016

Introduction

Fire plays an important role in forest ecosystems. Fire affects forest productivity, composition and diversity, and the pools and fluxes of carbon (C) and nutrients including nitrogen (N) (e.g. Mitchell *et al.* 2012; Kolka *et al.* 2014). Forest fire emissions of carbon dioxide (CO_2) significantly contribute to global greenhouse gas (GHG) fluxes and potentially climate change (e.g. Sommers *et al.* 2014). Recent research indicates that anthropogenic woodland and savanna fires produce ~0.93 Pg C year^{-1}, which is ~29% of the emissions of the continent of Africa (Valentini *et al.* 2014). As soil N plays a critical role in vegetation and soil microbial dynamics and C sequestration, it is important to understand how forest fire affects soil N (e.g. Mitchell *et al.* 2012; Kolka *et al.* 2014). Climate change is predicted to increase fire frequency, extent and severity in forested ecosystems, leading to changes in forest C and N dynamics and C sequestration potential, including in fire-prone ecosystems in Africa (e.g. Sommers *et al.* 2014).

There is uncertainty in our understanding of the effect of forest fires on soil C and N. The effects of fire on soil C and N are highly variable, with some studies finding that soil C or N pools were lost from the forest floor, with no change in the mineral soils (e.g. Kolka *et al.* 2014). Others have found that fire reduced soil C and/or N pools in the forest floor, but increased C and/or N in the upper mineral soils (e.g. Poirier *et al.* 2014). Time since fire can influence soil C and N pools (e.g. Mabuhay *et al.* 2006; Hamman *et al.* 2008). In the early stages post fire, changes in soil C and N can be minimal as losses through erosion and leaching can be offset by deposition of organic matter by newly growing vegetation (Johnson and Curtis 2001; Kaye *et al.* 2010). However, as time increases after fire, increases in both soil C and N through inputs from litterfall and root turnover lead to sequestration of soil C and N (Johnson and Curtis 2001; Kaye *et al.* 2010). Combined, these results suggest that further studies should consider assessing the effect of forest fire on forest floor and mineral soil C and N across a gradient of time since fire.

Unfortunately, little research on fire impacts on soil C and N has been conducted in sub-Saharan Africa in spite of frequent fires in the region (Archibald *et al.* 2012). Among the 75 papers used for a recent meta-analysis of the impact of forest fires on soils (Wang *et al.* 2012), three studies (Jensen *et al.* 2001; Andersson *et al.* 2004; Michelsen *et al.* 2004) were conducted in sub-Saharan Africa, none of which assessed soil C and N. Therefore, there is a need to conduct fire research to improve our understanding of the impact of forest fire on soil C and N pools in sub-Saharan Africa.

To improve our understanding, one area of urgently needed research is to assess how traditional fire management influences

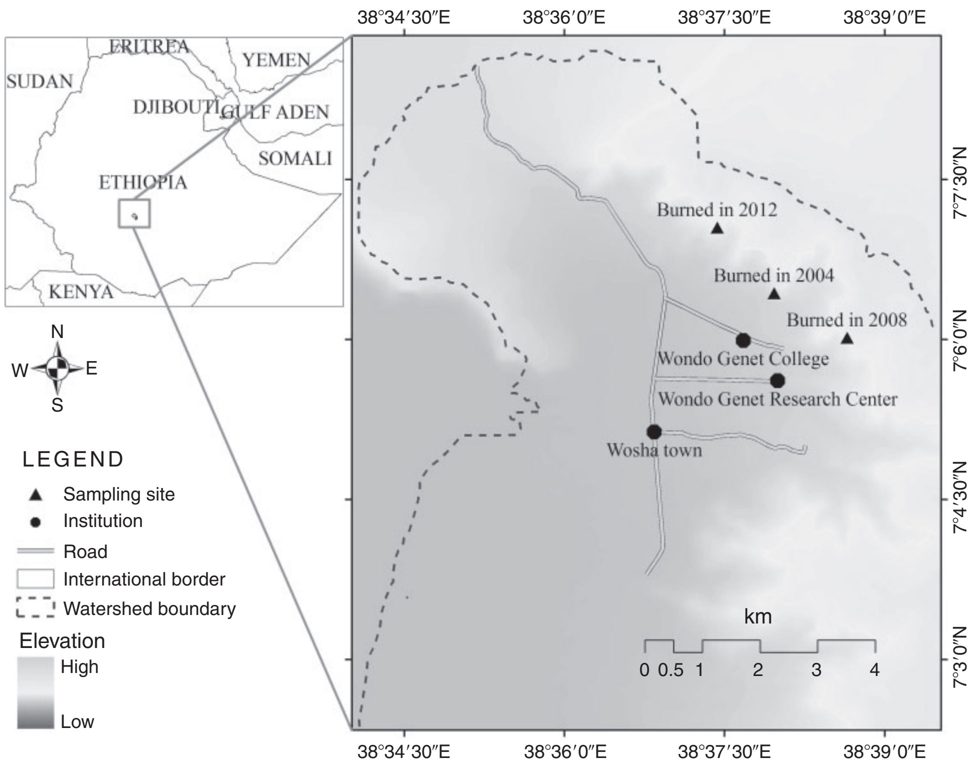

Fig. 1. Map of the study site. Sites are those burned in 2012 (B1-UB), 2008 (B5-UB) and 2004 (B9-UB) (B, burned; UB, unburned).

soil C and N dynamics in sub-Saharan Africa. Fire has been used in African landscapes to improve pasture for livestock for thousands of years (e.g. Bowman *et al.* 2009; Archibald *et al.* 2012). Essentially, traditional fire management converts forest to more open pasture land, encouraging low-stature forage species. More recently, traditional fire management has been perceived as an artificial disturbance causing deforestation and degradation and, as a result, has often been banned through restrictive legislation (e.g. Pyne 2001; Bowman *et al.* 2011). However, there is a renewed interest in using traditional fire management for ecosystem management (e.g. Johansson *et al.* 2012; Russell-Smith *et al.* 2013; Johansson and Granström 2014). Further studies are needed to assess how traditional fire management influences soil C and N dynamics, which ultimately affect ecosystem sustainability.

Wondo Genet Forest is a montane forest located in the Central Rift Valley of Ethiopia. The forest has been subjected to traditional fire management by local pastoral communities to improve pasture forage for grazing. Fire event dates for the past 20 years were recorded at the adjacent Wondo Genet College. Our objective was to assess the impact of traditional fire management on forest floor and soil C and N dynamics by comparing burned areas with adjacent unburned areas, and if time since fire (1, 5 and 9 years post fire) influenced this relationship. We hypothesised that traditional fire management would significantly decrease forest floor and upper mineral soil C and N pools but that the decrease would become less evident over time and with depth when compared with unburned systems.

Methods and materials

Study site description

Wondo Genet Forest is located at 7°06′N and 38°37′E and is part of the eastern escarpment of the Central Rift Valley of Ethiopia (Fig. 1). It is located ~260 km south of the capital city, Addis Ababa, and the forest lies within the altitudinal range of 1860–2580 m above sea level (a.s.l.). The study area has a sub-humid tropical climate and receives a mean annual rainfall of 1247 mm (Teklay and Malmer 2004). The rainfall pattern is bimodal, with a short rainy season between March and May accounting for 28% of total rainfall, and a long rainy season between July and October accounting for more than 50% of total rainfall (Teklay and Malmer 2004). The mean monthly temperature is 19.5°C with mean monthly maximum and minimum temperatures of 26.3 and 12.4°C respectively (Teklay and Malmer 2004). The bedrock in the area is mainly of basaltic composition, often overlain by volcanic ash deposits from the late Tertiary period and it is dominated with well-drained sandy loam to loam soils of high permeability classified as Mollic Andosols (FAO 1988). The top layer of the mineral soil (0–10-cm depth) has a pH (in H_2O) of 6.0–6.1 and cation exchange capacity of 19.7–21.7 meq per 100 g soil as determined by the ammonium acetate (pH 7) method (Teklay and Malmer 2004).

Three paired burned–unburned areas were selected that included a chronosequence of time since fire (Table 1). The first site (hereafter B9-UB for 9 years after burned–unburned) had a fire event in 2004, the second site (hereafter B5-UB for 5 years after burned–unburned) had a fire event in 2008, and the third site (hereafter B1-UB for 1 year after burned–unburned)

Table 1. Summary of study site description
B, burned; UB, unburned; m a.s.l., m above sea level

Site name	Location and altitude	Year of fire	Years since fire	Size of burned areas (ha)[A]	Dominant vegetation
B1-UB (1 year after burned–unburned)	7°07′03″N and 38°37′26″E, 1976 m a.s.l.	2012	1	3	Burned area: *Syzygium guineense* and *Combretum molle*; Unburned area: *Buddleja polystachya* Fresen and *Syzygium guineense*
B5-UB (5 years after burned–unburned)	7°06′01″N and 38°38′39″E, 2067 m a.s.l.	2008	5	1	Burned area: *Calpurnia aurea* and *Celtis Africana*; Unburned area: *Rhus vulgaris*, *Calpurnia aurea* and *Vernonia amygdalina*
B9-UB (9 years after burned–unburned)	7°06′26″N and 38°37′58″E, 1911 m a.s.l.	2004	9	3	Burned area: *Protea gaguedi*, *Nuxia congesta* and *Dodonaea angustifolia*; Unburned area: *Albizia gummifera*, *Calpurnia aurea* and *Croton macrostachyus*

[A]Estimated based on interview with locals owing to no official record on size of burned areas.

had a fire event in 2012 (Table 1). From interviewing 10 local residents, we found that it was unlikely there had been fires within the last 50 years before the fires in the study. The three sites were ~1.5 km from each other and had dominant vegetation that varied across paired burned and unburned areas and across sites (Fig. 1 and Table 1). Five soil sampling plots were randomly selected in each paired burned and unburned site inside areas (minimum 10-m distance between plots) that were known to be burned and unburned (i.e. no edge effects).

Forest floor and mineral soil sampling and analysis

For the forest floor, a soil sampling plot (1 m^2) was installed at the centre of each of the five randomly selected plots in burned–unburned paired treatments. The entire organic layer of the forest floor was collected after removing wood debris. After collecting the forest floor, the depth of the forest floor was measured. A soil profile was excavated from 0 to 100-cm depth at each soil sampling plot. From the soil pedon, soil was collected with a core sampler (5-cm diameter) from 0–10-, 10–20-, 20–40-, 40–70- and 70–100-cm soil depths at B5-UB. Soil was collected from 0–10, 10–20, 20–40 and 40–70 cm at B1-UB and B9-UB owing to large rocks below 70-cm soil depth. The soil samples from the core were used to determine soil bulk density and the samples from the soil pedon were used to determine soil organic carbon (SOC) and soil total nitrogen (STN) concentration. Bulk density of the forest floor and mineral soil was determined by dividing the oven-dry mass (40°C for forest floor, 105°C for mineral soils) by the soil volume (Grossman and Reinsch 2002). Forest floor subsamples were ground to a fine powder. Mineral soil subsamples were sieved (2 mm) and ground. Forest floor and soil subsamples were analysed for organic carbon (OC) concentration using the Walkley–Black titration method (Walkley and Black 1934; Nelson and Sommers 1996) and for total nitrogen (TN) concentration using the Kjeldahl method (Bremner and Mulvaney 1982). Organic carbon and TN pools in forest floor and mineral soils were calculated using the following Eqn 1:

$$P = (z \times \rho_b \times c) \times 10 \quad (1)$$

where P = OC or TN pools (g m^{-2}; 100 × g m^{-2} = Mg ha^{-1}) of the forest floor or mineral soils, z = thickness of the forest floor or mineral soils (cm), ρ_b = bulk density (g cm^{-3}) of the forest floor or mineral soils, and c = OC or TN concentration (g kg^{-1}) of the forest floor or mineral soils.

To determine SOC and STN pools for 0- to 100-cm depth, SOC and STN pools of each sample depth (0–10, 10–20, 20–40, 40–70, and 70–100 cm) were determined and the values were summed.

Statistical analysis

For all datasets, the normality of the distribution of the data was first analysed using the Shapiro–Wilk normality test (Shapiro and Wilk 1965). Paired *t*-tests (McDonald 2014) were used to test for differences (at the $P < 0.05$ level) between paired burned and unburned forest floor and mineral SOC and STN concentrations, pools and SOC : STN (hereafter C : N) ratio both within sites and across the chronosequence. When the standard assumptions of normality were violated, a Mann–Whitney rank sum test (Mann and Whitney 1947) was used. These statistical analyses were conducted using *SAS ver. 9.2*.

We recognised that the study design is pseudoreplicated because there was only one paired site per time since fire. It would have been more defensible to have multiple paired sites per time since fire but no additional sites occurred in our study area. Conclusions can only be drawn about the effects of traditional fire management on SOC and STN in the Wondo Genet area of Ethiopia.

Results

Across study sites, regardless of burned or unburned status, SOC and STN contents and C : N ratios commonly showed a decreasing pattern with depth (Table 2). Forest floor OC and TN concentrations and pools and C : N ratio were not significantly different between paired burned and unburned areas or across the chronosequence (Table 2). Mineral SOC concentration was not significantly different in soil layers in paired burned and unburned areas in B1-UB and B9-UB (Table 2). However, in B5-UB, SOC concentration was significantly higher in burned areas in deeper soil depths at 40–70-cm (difference: 54.6%, $n = 5$, $P = 0.016$) and 70–100-cm (difference: 19.7%, $n = 5$, $P = 0.016$) layers compared with those in the unburned area

Table 2. Summary of organic carbon (OC) and total nitrogen (TN) concentrations and pools, and OC concentration

TN concentration (hereafter C : N) ratio in forest floor and mineral soils at B1-UB (1 year after burned–unburned), B5-UB (5 years after burned–unburned) and B9-UB (9 years after burned–unburned). Shown are mean ± standard error ($n = 5$). ND, no data. In 'Diff.' column, '–' signifies no significant difference

Item	Layer (cm)	UB adjacent to B9	B9	Diff. (%)[A]	UB adjacent to B5	B5	Diff. (%)	UB adjacent to B1	B1	Diff. (%)
OC content	Forest floor[C]	67.3 ± 3.1	73.6 ± 6.5	–	45.5 ± 4.5	44.6 ± 3.6	–	59.1 ± 7.0	62.7 ± 8.5	–
($g\ kg^{-1}$)	0–10	50.9 ± 9.5	48.9 ± 6.1	–	65.3 ± 4.4	52.3 ± 3.5	–	50.0 ± 3.5	48.4 ± 8.1	–
	10–20	34.3 ± 4.7	35.4 ± 2.6	–	35.7 ± 2.9	32.3 ± 5.2	–	25.8 ± 2.3	32.9 ± 5.2	–
	20–40	29.7 ± 6.2	27.3 ± 1.4	–	26.9 ± 4.3	16.6 ± 1.6	–	17.9 ± 2.5	23.9 ± 3.5	–
	40–70	24.1 ± 10.0	18.1 ± 3.7	–	13.7 ± 0.7	8.9 ± 0.2	54.6[B]	13.0 ± 1.6	18.6 ± 2.5	–
	70–100	ND	ND	–	8.3 ± 0.2	6.9 ± 0.3	19.7[B]	ND	ND	–
OC pools	Forest floor	28.3 ± 2.9	28.9 ± 2.3	–	23.4 ± 7.7	19.4 ± 8.9	–	22.9 ± 8.6	29.7 ± 9.6	–
($Mg\ ha^{-1}$)	Mineral soil	126.8 ± 16.1	143.7 ± 6.2	–	143.5 ± 14.6	99.9 ± 7.3	–	84.8 ± 7.9	95.3 ± 11.9	–
TN content	Forest floor	5.2 ± 0.3	5.8 ± 0.6	–	3.1 ± 0.2	3.6 ± 0.5	–	4.2 ± 0.0.6	4.4 ± 0.0.6	–
($g\ kg^{-1}$)	0–10	3.6 ± 0.7	3.8 ± 0.5	–	7.3 ± 1.1	8.1 ± 1.7	–	4.4 ± 0.0.9	3.4 ± 0.5	–
	10–20	2.4 ± 0.3	2.5 ± 0.2	–	4.2 ± 0.8	4.3 ± 0.9	–	3.0 ± 1.1	2.6 ± 0.4	–
	20–40	2.2 ± 0.4	2.1 ± 0.1	–	2.4 ± 0.4	2.1 ± 0.5	–	1.9 ± 0.6	1.8 ± 0.3	
	40–70	1.8 ± 0.6	1.4 ± 0.2	–	1.3 ± 0.0	1.4 ± 0.3	–	1.1 ± 0.1	1.4 ± 0.2	–
	70–100	ND	ND	–	1.0 ± 0.1	0.8 ± 0.0	–	ND	ND	–
TN pools	Forest floor	2.2 ± 0.3	2.2 ± 0.4	–	1.6 ± 0.1	1.6 ± 0.3	–	1.6 ± 0.2	2.1 ± 0.3	–
($Mg\ ha^{-1}$)	Mineral soil	9.1 ± 1.0	10.8 ± 0.3	–	13.2.8 ± 1.2	10.1 ± 0.6	–	6.3 ± 0.5	7.2 ± 0.8	–
C : N	Forest floor	13.1 ± 0.3	12.9 ± 0.7	–	14.7 ± 0.5	12.9 ± 0.9	–	14.1 ± 0.4	14.4 ± 0.3	–
	0–10	14.3 ± 0.3	12.8 ± 0.1	11.7[B]	10.4 ± 0.3	9.8 ± 0.7	–	14.1 ± 0.3	14.1 ± 0.3	–
	10–20	14.1 ± 0.2	14.1 ± 0.4	–	10.2 ± 0.3	9.2 ± 0.3	10.5[B]	13.7 ± 0.6	12.6 ± 0.2	–
	20–40	13.3 ± 0.8	13.2 ± 0.5	–	11.0 ± 0.5	10.2 ± 0.3	–	12.7 ± 0.2	13.0 ± 0.3	–
	40–70	13.0 ± 1.2	12.7 ± 1.0	–	10.2 ± 0.6	8.6 ± 0.1	–	11.9 ± 0.6	13.8 ± 0.9	–
	70–100	ND	ND	–	8.4 ± 0.5	8.3 ± 0.5	–	ND	ND	–

[A] Difference (Diff.) (%) = (B9, B5 or B1 – UB)/UB × 100.

[B] $P < 0.05$.

[C] Thickness of forest floor (mean ± standard error, $n = 5$): UB adjacent to B9, 3.4 ± 0.2 cm; B9, 4.2 ± 0.4 cm; UB adjacent to B5, 3.8 ± 0.6 cm; B5 burned, 2.6 ± 0.4 cm; UB adjacent to B1, 2.8 ± 0.4 cm; B1, 2.4 ± 0.5 cm.

(Table 2). Soil organic carbon pools were not significantly different between paired burned and unburned areas or across the chronosequence when combining all soil depths, or at individual depth increments (Table 2). Mineral STN concentration and pools were not significantly different in paired burned and unburned areas or across the chronosequence when combining all depths or at individual depth increments (Table 2). Mineral soil C : N was significantly higher in the burned area at 0–10-cm depth at B9-UB (difference: 11.7%, $n = 5$, $P = 0.036$) and at 10–20-cm soil depth in B5-UB (difference: 10.5%, $n = 5$, $P = 0.036$) when compared with the paired unburned area (Table 2). No other differences were observed in mineral soil C : N ratio across paired burned or unburned areas with depth or across the chronosequence.

Discussion

Contrary to our hypotheses, our results indicate that despite differences in time since fire and dominant post-fire vegetation, forest floor and mineral soil OC and TN pools were not significantly different between burned and unburned pairs or across sites. The results suggest that the forest fires set by local communities as their practice of traditional fire management did not affect forest floor and mineral soil OC and TN pools. Our results are in line with other studies indicating no effect or little effect of fire on mineral SOC and STN pools (e.g. Kolka *et al.* 2014; Maynard *et al.* 2014). Also meta-analyses by Nave *et al.* (2011), Wan *et al.* (2001), Johnson and Curtis (2001) and Boerner *et al.* (2009) found that prescribed fire, such as that used in traditional fire management, did not have significant overall effects on either mineral SOC or STN, because prescribed fires tend to be implemented under fairly low fuel loads and weather conditions (Nave *et al.* 2011). Combustion of mineral SOC begins at 200 to 250°C, with complete combustion at ~460°C (Giovannini *et al.* 1988). It is inferred that the burned mineral soils never experienced temperatures high enough for oxidation.

The only difference we detected was an increase in SOC concentration in the 40–100-cm depth in the burned area of B5-UB. Given the depth, we do not believe the difference was a result of fire but other soil processes that affect carbon concentrations at depth (e.g. root exudates). It is unlikely that fire affected SOC concentration in deep soil layers without causing any impact on surface and shallow soil layers. However, somewhat similarly to our results at site B5-UB, in western Ethiopia, fire in frequently burned wooded grasslands led to small increases in SOC concentrations from upper soils to deeper soil layers whereas SOC decreased from surface soils to deeper layer in less frequently burned forest and wooded grasslands (Michelsen *et al.* 2004). In our case, though, we also saw decreases in SOC concentration with depth similar to the less frequently burned forest and wooded grasslands. Other studies have found increases in mineral SOC concentrations following fire (e.g. Knicker *et al.* 2005; Miesel *et al.* 2012). The increase can be attributed to the input of partly charred material or litter from decaying trees (Knicker 2007; DeLuca and Aplet 2008) that have high C : N ratios. Also, the disturbance of the soil caused by fire can increase the mobility of dissolved organic carbon and promote SOC stabilisation at depth by association with fine particles (Schelker *et al.* 2012; Poirier *et al.* 2014).

The observed higher soil C : N in the burned area compared with the unburned areas B5-UB (10–20-cm depth) and in B9-UB (0–10-cm depth) is surprising considering that other studies have found lower short-term C : N ratios following fire (Yermakov and Rothstein 2006; Kolka *et al.* 2014). Our sites are 5 and 9 years post fire and we suspect that plant uptake of N following fire was higher than in unburned areas as a result of vegetation regrowth following fire or possibly that N (in nitrate form) was preferentially leached relative to C post fire.

Similarly to our results, global syntheses by Nave *et al.* (2011) and Wang *et al.* (2012) found no significant impact of prescribed fire on mineral SOC or STN concentrations whereas wildfire significantly decreased SOC and increased STN concentrations, although not affecting overall pools in the case of Nave *et al.* (2011). As a result, Nave *et al.* (2011) suggested that averting wildfires through prescribed burning is desirable from a soils perspective.

Our results support the current reassessment of the role of traditional fire management in savanna and forest management. In north Australian savannas, the traditional anthropogenic fire regime was reintroduced to abate the higher C release from wildfires (e.g. Fitzsimons *et al.* 2012; Russell-Smith *et al.* 2013). In forested montane heathland ecosystems in southern Ethiopia, pastoralists use fire to improve pasture, to remove insect pests and to reduce livestock loss to predators (Johansson *et al.* 2012; Johansson and Granström 2014). Moreover, it has been suggested that fire exclusion is not a valid option for the heathlands because it would degrade pasture quality and highly flammable vegetation would develop, providing potential for reoccurring severe wildfires (Johansson *et al.* 2012). Further studies are needed to assess various aspects of traditional fire management in terms of ecosystem health and sustainability. For example, studies are needed to assess the impact of traditional fire management on GHG emissions and effects on plant and animal biodiversity.

Acknowledgements

The authors wish to thank Teferi Shanka for assisting with field and laboratory work. We are also grateful to Tefera Mengistu for his valuable comments on the research design. Financial support was provided by the Office of Research and Technology Transfer, Wondo Genet College of Forestry and Natural Resources, Hawassa University.

References

Andersson M, Michelsen A, Jensen M, Kjøller A (2004) Tropical savannah woodland: effects of experimental fire on soil microorganisms and soil emissions of carbon dioxide. *Soil Biology & Biochemistry* **36**, 849–858. doi:10.1016/J.SOILBIO.2004.01.015

Archibald S, Staver AC, Levin SA (2012) Evolution of human-driven fire regimes in Africa. *Proceedings of the National Academy of Sciences of the United States of America* **109**, 847–852. doi:10.1073/PNAS.1118648109

Boerner REC, Hart S, Huang J (2009) Impacts of fire and fire surrogate treatments. *Ecological Applications* **19**, 338–358. doi:10.1890/07-1767.1

Bowman DMJS, Balch JK, Artaxo P, Bond WJ, Carlson JM, Cochrane MA, D'Antonio CM, DeFries RS, Doyle JC, Harrison SP, Johnston FH, Keeley JE, Krawchuk MA, Kull CA, Marston JB, Moritz MA, Prentice IC, Roos CI, Scott AC, Swetnam TW, van der Werf GR, Pyne SJ (2009) Fire in the Earth system. *Science* **324**, 481–484. doi:10.1126/SCIENCE.1163886

Bowman DMJS, Balch J, Artaxo P, Bond WJ, Cochrane MA, D'Antonio CM, DeFries R, Johnston FH, Keeley JE, Krawchuk MA, Kull CA, Mack M, Moritz MA, Pyne S, Roos CI, Scott AC, Sodhi NS, Swetnam TW (2011) The human dimension of fire regimes on Earth. *Journal of Biogeography* **38**, 2223–2236. doi:10.1111/J.1365-2699.2011.02595.X

Bremner JM, Mulvaney CS (1982) Nitrogen – total. In 'Methods of soil analysis, Part 2. Chemical and microbiological properties', 2nd edn. (Eds AL Page, RH Miller, DR Keeney) pp. 595–624. (Soil Science Society of America, Inc. and American Society of Agronomy, Inc.: Madison, WI)

DeLuca TH, Aplet GH (2008) Charcoal and carbon storage in forest soils of the Rocky Mountains West. *Frontiers in Ecology and the Environment* **6**, 18–24. doi:10.1890/070070

FAO (1988) World reference base for soil resources. World Soil Resources Reports 84. (Food and Agricultural Organization of the United Nations: Rome, Italy)

Fitzsimons J, Russell-Smith J, James G, Vigilante T, Lipsett-Moore G, Morrison J, Looker M (2012) Insights into the biodiversity and social benchmarking components of the northern Australian fire management and carbon abatement programmes. *Ecological Management & Restoration* **13**, 51–57. doi:10.1111/J.1442-8903.2011.00624.X

Giovannini G, Lucchesi S, Giachetti M (1988) Effects of heating on some physical and chemical parameters related to soil aggregation and erodibility. *Soil Science* **146**, 255–261. doi:10.1097/00010694-198810000-00006

Grossman RB, Reinsch TG (2002) Bulk density and linear extensibility. In 'Methods of soil analysis, Part. 4. Physical methods'. (Eds JH Dane, GC Topp) pp. 201–254. (Soil Science Society of America, Inc. and American Society of Agronomy, Inc.: Madison, WI)

Hamman ST, Burke IC, Knapp EE (2008) Soil nutrients and microbial activity after early and late season prescribed burns in a Sierra Nevada mixed-conifer forest. *Forest Ecology and Management* **256**, 367–374. doi:10.1016/J.FORECO.2008.04.030

Jensen M, Michelsen A, Gashaw M (2001) Responses in plant, soil inorganic and microbial nutrient pools to experimental fire, ash and biomass addition in a woodland savanna. *Oecologia* **128**, 85–93. doi:10.1007/S004420000627

Johansson MU, Granström A (2014) Fuel, fire and cattle in African highlands: traditional management maintains a mosaic heathland landscape. *Journal of Applied Ecology* **51**, 1396–1405. doi:10.1111/1365-2664.12291

Johansson MU, Fetene M, Malmer A, Granström A (2012) Tending for cattle: traditional fire management in Ethiopian montane heathlands. *Ecology and Society* **17**, 19. doi:10.5751/ES-04881-170319

Johnson DW, Curtis PS (2001) Effects of forest management on soil C and N storage: meta-analysis. *Forest Ecology and Management* **140**, 227–238. doi:10.1016/S0378-1127(00)00282-6

Kaye JP, Romanyà J, Vallejo VR (2010) Plant and soil carbon accumulation following fire in Mediterranean woodlands in Spain. *Oecologia* **164**, 533–543. doi:10.1007/S00442-010-1659-4

Knicker H (2007) How does fire affect the nature and stability of soil organic nitrogen and carbon? A review. *Biogeochemistry* **85**, 91–118. doi:10.1007/S10533-007-9104-4

Knicker H, González-Vila FJ, Polvillo O, González JA, Almendros G (2005) Fire induced transformation of C- and N-forms in different organic soil fractions from a Dystric Cambisol under a Mediterranean pine forest (*Pinus pinaster*). *Soil Biology & Biochemistry* **37**, 701–718. doi:10.1016/J.SOILBIO.2004.09.008

Kolka R, Sturtevant B, Townsend P, Miesel J, Wolter P, Fraver S, DeSutter T (2014) Post-fire comparisons of forest floor and soil carbon, nitrogen, and mercury pools with fire severity indices. *Soil Science Society of America Journal* **78**, S58–S65. doi:10.2136/SSSAJ2013.08.0351NAFSC

Mabuhay JA, Isagi Y, Nakagoshi N (2006) Wildfire effects on microbial biomass and diversity in pine forests at three topographic positions. *Ecological Research* **21**, 54–63. doi:10.1007/S11284-005-0094-1

Mann HB, Whitney DR (1947) On a test of whether one of two random variables is stochastically larger than the other. *Annals of Mathematical Statistics* **18**, 50–60. doi:10.1214/AOMS/1177730491

Maynard DG, Paré D, Thiffault E, Lafleur B, Hogg KE, Kishchuk B (2014) How do natural disturbances and human activities affect soils and tree nutrition and growth in the Canadian boreal forest? *Environmental Review* **22**, 161–178. doi:10.1139/ER-2013-0057

McDonald JH (2014) 'Handbook of Biological Statistics', 3rd edn. (Sparky House Publishing: Baltimore, MD)

Michelsen A, Andersson M, Jensen M, Kjøller A, Gashew M (2004) Carbon stocks, soil respiration and microbial biomass in fire-prone tropical grassland, woodland and forest ecosystems. *Soil Biology & Biochemistry* **36**, 1707–1717. doi:10.1016/J.SOILBIO.2004.04.028

Miesel JR, Goebel PC, Corace RG, Hix DM, Kolka R, Palik B, Mladenoff D (2012) Fire effects on soils in Lake States forests: a compilation of published research to facilitate long-term investigations. *Forests* **3**, 1034–1070. doi:10.3390/F3041034

Mitchell CP, Kolka RK, Fraver S (2012) Singular and combined effects of blowdown, salvage logging, and wildfire on forest floor and soil mercury pools. *Environmental Science & Technology* **46**, 7963–7970. doi:10.1021/ES300133H

Nave LE, Vance ED, Swanston CW, Curtis PS (2011) Fire effects on temperate forest soil C and N storage. *Ecological Applications* **21**, 1189–1201. doi:10.1890/10-0660.1

Nelson DW, Sommers LE (1996) Total carbon, organic carbon, and organic matter. In 'Methods of soil analysis, Part 3. Chemical methods'. (Eds DL Sparks, AL Page, PA Helmke, RH Loeppert, PN Soluanpour, MA Tabatabai, CT Johnston, ME Sumner) pp. 961–1010. (Soil Science Society of America, Inc. and American Society of Agronomy, Inc.: Madison, WI)

Poirier V, Paré D, Boiffin J, Munson AD (2014) Combined influence of fire and salvage logging on carbon and nitrogen storage in boreal forest soil profiles. *Forest Ecology and Management* **326**, 133–141. doi:10.1016/J.FORECO.2014.04.021

Pyne SJ (2001) The fires this time, and next. *Science* **294**, 1005–1006. doi:10.1126/SCIENCE.1064989

Russell-Smith J, Cook GD, Cooke PM, Edwards AC, Lendrum M, Meyer CP, Whitehead PJ (2013) Managing fire regimes in north Australian savannas: applying Aboriginal approaches to contemporary global problems. *Frontiers in Ecology and the Environment* **11**, e55–e63. doi:10.1890/120251

Schelker J, Eklöf K, Bishop K, Laudon H (2012) Effects of forestry operations on dissolved organic carbon concentrations and export in boreal first-order streams. *Journal of Geophysical Research* **117**, G01011. doi:10.1029/2011JG001827

Shapiro SS, Wilk MB (1965) An analysis of variance test for normality (complete samples). *Biometrika* **52**, 591–611. doi:10.1093/BIOMET/52.3-4.591

Sommers WT, Loehman RA, Hardy CC (2014) Wildland fire emissions, carbon, and climate: science overview and knowledge needs. *Forest Ecology and Management* **317**, 1–8. doi:10.1016/J.FORECO.2013.12.014

Teklay T, Malmer A (2004) Decomposition of leaves from two indigenous trees of contrasting qualities under shaded-coffee and agricultural land-uses during the dry season at Wondo Genet, Ethiopia. *Soil Biology & Biochemistry* **36**, 777–786. doi:10.1016/J.SOILBIO.2003.12.013

Valentini R, Arneth A, Bombelli A, Castaldi S, Cazzolla Gatti R, Chevallier F, Ciais P, Grieco E, Hartmann J, Henry M (2014) A full greenhouse gases budget of Africa: synthesis, uncertainties, and vulnerabilities. *Biogeosciences* **11**, 381–407. doi:10.5194/BG-11-381-2014

Walkley A, Black IA (1934) An examination of the Degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method. *Soil Science* **37**, 29–38. doi:10.1097/00010694-193401000-00003

Wan S, Hui D, Luo Y (2001) Fire effects on nitrogen pools and dynamics in terrestrial ecosystems: a meta-analysis. *Ecological Applications* **11**, 1349–1365. doi:10.1890/1051-0761(2001)011[1349:FEONPA]2.0.CO;2

Wang Q, Zhong M, Wang S (2012) A meta-analysis on the response of microbial biomass, dissolved organic matter, respiration, and N mineralization in mineral soil to fire in forest ecosystems. *Forest Ecology and Management* **271**, 91–97. doi:10.1016/J.FORECO.2012.02.006

Yermakov Z, Rothstein DE (2006) Changes in soil carbon and nitrogen cycling along a 72-year wildfire chronosequence in Michigan jack pine forests. *Oecologia* **149**, 690–700. doi:10.1007/S00442-006-0474-4