Minor changes in soil organic carbon and charcoal concentrations detected in a temperate deciduous forest a year after an experimental slash-and-burn

E. Eckmeier, R. Gerlach, J. O. Skjemstad, O. Ehrmann, M. W. I. Schmidt

Biogeosciences, 4, 377–383, 2007
www.biogeosciences.net/4/377/2007/

Biogeosciences

Minor changes in soil organic carbon and charcoal concentrations detected in a temperate deciduous forest a year after an experimental slash-and-burn

E. Eckmeier[1], **R. Gerlach**[2], **J. O. Skjemstad**[3], **O. Ehrmann**[4], **and M. W. I. Schmidt**[1]

[1]University of Zurich, Department of Geography, Winterthurerstrasse 190, 8057 Zurich, Switzerland
[2]Rheinisches Amt für Bodendenkmalpflege, Endenicher Str. 133, 53115 Bonn, Germany
[3]CSIRO Land and Water, PMB 2, Glen Osmond, SA 5064, Australia
[4]Münster 12, 97933 Creglingen, Germany

Received: 30 January 2007 – Published in Biogeosciences Discuss.: 15 February 2007
Revised: 3 May 2007 – Accepted: 5 June 2007 – Published: 22 June 2007

Abstract. Anthropogenic fires affected the temperate deciduous forests of Central Europe over millennia. Biomass burning releases carbon to the atmosphere and produces charcoal, which potentially contributes to the stable soil carbon pools and is an important archive of environmental history. The fate of charcoal in soils of temperate deciduous forests, i.e. the processes of charcoal incorporation and transportation and the effects on soil organic matter are still not clear. We investigated the effects of slash-and-burn at a long-term experimental burning site and determined soil organic carbon and charcoal carbon concentrations as well as the soil lightness of colour (L*) in the topmost soil material (0–1, 1–2.5 and 2.5–5 cm depths) before, immediately after the fire and one year later. The main results are that (i) only a few of the charcoal particles from the forest floor were incorporated into the soil matrix, presumably by soil mixing animals. In the 0–1 cm layer, during one year, the charcoal C concentration increased only by 0.4 g kg^{-1} and the proportion of charcoal C to SOC concentration increased from 2.8 to 3.4%; (ii) the SOC concentrations did not show any significant differences; (iii) soil lightness decreased significantly in the topmost soil layer and correlated well with the concentrations of charcoal C (r=−0.87**) and SOC (r=−0.94**) in the samples from the 0–5 cm layer. We concluded that Holocene biomass burning could have influenced soil charcoal concentrations and soil colour.

Correspondence to: E. Eckmeier
(eckmeier@geo.unizh.ch)

1 Introduction

Palaeobotanical records indicate that anthropogenic fires were common in the past and might have been deliberately used for hunting, herding or farming. Fire-clearance husbandry, or slash-and-burn, was used for landscape management and agriculture from the prehistoric Mesolithic until the modern 19th century and thus may have affected the global carbon cycle during the last 10 000 years (Anderson, 1994; Pyne, 1994; Carcaillet et al., 2002; Tinner et al., 2005).

Anthropogenic burning had the highest impact on the landscape during the Late-Neolithic (3500–2200 BC) when the natural landscape of Central Europe was transformed into a cultural landscape, and new regions were able to be colonized using the fertilizing and clearing effects of burning (W. Schier, personal communication; Lüning, 2000; Kalis et al., 2003). The first evidence for Neolithic agricultural burning came from Northern Germany and Denmark where burning accompanied the transition from Mesolithic to Neolithic agricultural techniques since 4000 BC (Iversen, 1941; Kalis and Meurers-Balke, 1998). Clark et al. (1989) reported that farmers in Late to End Neolithic (4400–2200 BC) used fire to transform forest into arable land. Shifting cultivation with slash-and-burn was proposed by Rösch (1993, 2000) for the pre-alpine lowlands during the Late Neolithic period (4300–3500 BC). Charcoal records from the Swiss midlands and alpine regions suggested that the burning of forest to gain arable land or meadows occurred not only in Neolithic but also in Bronze and Iron Age (Gobet et al., 2003; Tinner et al., 2005). Fire-fallow silviculture has been used until modern times, e.g. in the Black Forest to encourage oaks for tannic acid (Goldammer et al., 1997) or in Southern Switzerland to enhance the cultivation of chestnut trees (Conedera et al., 2004).

Published by Copernicus Publications on behalf of the European Geosciences Union.

Table 1. Soil properties of the investigated Haplic Luvisol in the Forchtenberg experimental site (data provided by L. Herrmann).

Horizon	Depth	Sand	Silt	Clay	pH	C/N
	cm		$g\,kg^{-1}$		$CaCl_2$	
Ah	0–16	40	810	150	3.9	12
E	16–54	40	800	160	4.0	10
Bt	54–104	20	750	230	4.6	5
Bvt	104–151	20	790	190	5.3	5
Bv	151–179	10	800	190	5.8	5

Biomass burning releases an estimated 2.5 Pg atmospheric carbon per year (van der Werf et al., 2006). Vegetation fires also produce charcoal or black carbon, which are part of a continuum of material generated during incomplete combustion of biomass (Kuhlbusch, 1998). Although recent investigations have shown that microbes can degrade black carbon (Hamer et al., 2004; Hockaday et al., 2006), it still contributes to the slow carbon pools in soils (Skjemstad et al., 2004). Biomass burning could affect the soil carbon stocks, as modelled for the boreal system (Harden et al., 2000) but field observations and experimental studies are rare and have been conducted mainly in savannah, tropical or boreal forests (Forbes et al., 2006). Long-term observations, after burning, have revealed all possible variations: either no changes in soil organic carbon stocks (Roscoe et al., 2000; Dai et al., 2005), a reduction (Bird et al., 2000) or an increase (Ojima et al., 1994). However, the data about soil carbon and charcoal and their dynamics in the soil profile after a fire is limited and to our knowledge no quantitative assessment has been attempted in temperate deciduous forests (Preston and Schmidt, 2006).

The condensed aromatic structure of charcoal or black carbon allows charcoal particles to persist in soils and other sedimentary records over millennial time-scales and makes it possible to reconstruct environmental history and past forestfires (Patterson III et al., 1987; Willis and van Andel, 2004; Wang et al., 2005) or to infer pedological processes (Carcaillet et al., 2006). The interpretation of soil charcoal data needs an understanding of the taphonomical processes that affect charcoal particles but uncertainties still remain related to charcoal transport following a fire or charcoal burial and mixing within a soil profile.

Burning has an effect on soil colour; recent work has shown that the content of aromatic carbon, a carbon species which dominates the black carbon structure, correlated significantly with soil lightness (Spielvogel et al., 2004) and that black carbon might be responsible for the dark colour of Chernozem humus horizons (Schmidt et al., 2002). Onethird of the organic matter of fossil dark soil horizons embedded in lighter Haplic Luvisols consisted of black carbon derived from Holocene anthropogenic burning (Gerlach et al., 2006).

In this study, we investigated the influence of slash-and-burn in a temperate deciduous forest on soil organic carbon budgets as part of an experimental burning in Forchtenberg (SW-Germany; Rösch et al., 2002). The same experiment delivered data about the conversion of biomass fuel to charcoal during a slash-and-burn and the amount of charcoal left in the litter layer (Eckmeier et al., 2007).

Our main research questions in this study were: (i) How much of the charcoal produced during one fire (slash-and-burn) do we find in the soil mineral matrix after one year? (ii) Are the total soil organic carbon concentrations affected by the fire? (iii) Does the soil colour change and does it correlate with the soil charcoal carbon and soil organic carbon concentrations?

2 Materials and methods

2.1 Site description and burning technique

The burning took place in October 2004 on a trial site located near Forchtenberg (SW-Germany; 49°16′ N, 09°28′ E) on a slightly sloping (2–4%) and south-exposed plain (320 m a.s.l.). Mean annual temperature is 8.9°C, mean annual precipitation is 849 mm. On the day of burning the average temperature was 18.4°C and the average relative humidity was 71%.

The 3.5 ha area is situated in a temperate deciduous forest dominated by *Fagus*, *Acer* and *Carpinus* (Rösch et al., 2002). The undergrowth species are characteristic for a woodruff-beech forest (*Galio-Fagetum*). The area has been forested for at least two centuries; the trees are about 40 years old. The soil is an acidic Haplic Luvisol (WRB-FAO) with partly stagnic properties (Table 1). We investigated the changes in soil organic carbon and charcoal carbon concentrations of the topsoil material (Ah, 0–16 cm depth), which is followed by an eluviation horizon (E), an argic horizon with hydromorphic features (Bt), a cambic to argic horizon (Bvt) and a cambic horizon (Bv). The parent material is loamy loess over Triassic sandstone. Soil moisture was 30 vol. % on the day of burning.

After the trees were cut on a plot of 30×30 m (April 2004), the trunks and large branches (diameter >10 cm) were removed from the site. The smaller branches were allowed to dry over the summer. In autumn (October 2004) an area of 11×8 m was burnt. The dried wood was collected into a pile off the burning site and a row on the burning site. The wood in the row was ignited and drawn over the ground using long hooks for pulling and permanently supplemented with wood from the pile. This technique was applied to completely burn the grass and herbaceous vegetation and to distribute the charcoal and ash as homogeneously as possible. The temperatures in the soil during the burning were monitored at soil depths of 1, 2, 5 and 10 cm using six temperature

Table 2. Means and standard errors for soil samples taken before the burning (control), immediately after the burning (burnt) and one year after the burning (burnt 1 yr). The values are given for the three depths and the weighted average.

Sample		*n*	L*		SOC		Charcoal C		Charcoal C	Charcoal Mass[1]
	cm			*p*	g kg^{-1}	*p*	g kg^{-1}	*p*	% of SOC	g kg^{-1}
control	0–1	14	49.5±0.5		53.9±1.9		1.5±0.1		2.8	2.0
control	1–2.5	14	51.3±0.4		38.9±1.7		1.1±0.1		2.7	1.4
control	2.5–5	19	52.7±0.4		31.0±1.1		0.8±0.0		2.5	1.0
average[2]	0–5		51.6		37.9		1.0		2.6	1.3
burnt	0–1	17	47.9±0.2	0.124	55.2±1.7	0.925	1.6±0.1	0.802	3.0	2.1
burnt	1–2.5	17	50.3±0.3	0.397	39.5±1.2	0.826	1.1±0.1	0.925	2.8	1.4
burnt	2.5–5	19	52.5±0.3	0.904	29.7±1.1	0.629	0.8±0.1	0.872	2.6	1.0
average[2]	0–5		50.9		37.7		1.1		2.7	1.4
burnt 1 yr	0–1	20	46.3±0.3	0.009	55.2±1.1	0.975	1.9±0.1	0.363	3.4	2.5
burnt 1 yr	1–2.5	20	49.6±0.3	0.167	38.8±1.0	0.432	1.1±0.1	0.730	2.7	1.4
burnt 1 yr	2.5–5	20	53.0±0.2	0.546	26.8±0.7	0.147	0.6 (0.4)[3]±0.0	0.081	2.1	0.7
average[2]	0–5		50.6		36.0		1.0 (0.9)[3]		2.5	1.3

p-values refer to control samples. [1] calculated with average C concentration (775 g kg^{-1}) of charcoal particles in the litter layer (Eckmeier et al., 2007); [2] weighted average; [3] when normalized to the bulk density, the charcoal C concentrations change only in the bottom layer of the burnt 1yr sample set.

loggers. The maximum temperature measured was 72°C at 1 cm depth.

2.2 Soil sampling and analyses

Soil samples were collected in a random sample design in plastic tubes (6×4×15 cm) from the topsoil: 20 samples before burning (control), 20 samples immediately after the burning (burnt) and 20 samples one year after burning (burnt 1yr). They were cut into three depth intervals (0–1, 1–2.5, 2.5–5 cm) and dried at 40°C for 24 h. The aggregates were crushed and coarse material (roots and charcoal particles) >2000 μm was separated by sieving. Sub-samples were ground for carbon analyses.

Total carbon concentrations were determined for all soil samples by dry combustion via an elemental analyzer (Elementar VarioEL). The values for total organic carbon corresponded to the total carbon content because the soil samples did not contain carbonates.

The analysis of charred material in the soil samples was performed using mid infrared - Fourier transformed infrared spectroscopy (MIR-DRIFT; Viscarra Rossel et al., 2006; Janik et al., 2007). Samples were ground and measured directly and the spectra obtained were fitted with the calibration sample set (data collection CSIRO Land and Water, Adelaide). The soil properties were subsequently predicted using partial least-squares (PLS) analysis. For charcoal carbon concentrations the method reached a high correlation of R^2=0.86.

The soil colour was expressed as lightness (L*; Commission Internationale de l'Eclairage, CIE 1976 Standard Observer). The L* values indicate the extinction of light on a scale from L* 0 (absolute black) to L* 100 (absolute white). The soil samples were measured in triplicate using a photo spectrometer (Dr. Lange spectro-color) by observing the diffused reflected light under standardised observation conditions. We used dried and homogenized but not ground samples because grinding the soil material would increase the soil lightness (Torrent and Barrón, 1993).

For micromorphological analysis, undisturbed soil samples were collected with Kubiëna tins (8×6×4 cm). The blocks were air dried, impregnated with Palatal P80-21 polyester resin (BASF) and sliced into 75×55×0.3 mm thin-sections. The sections were described at 12.5–400× magnification under a petrological microscope. Detailed principles and methods used for micromorphological analysis have been described by Stoops (2003).

Data was statistically analysed using the Kolmogorov-Smirnov test for normal distribution. Because the data is not normally distributed, the Wilcoxon test was applied to compare paired samples, and the Spearman correlation (Sigma 2-tailed) to express significant correlations.

3 Results and discussion

3.1 Incorporation of charcoal from the forest floor into the soil mineral matrix

The charcoal carbon (C) concentrations decreased significantly with depth in all sample sets (p=0.000-0.004), as shown in Table 2. Immediately after the burning, 0.1 g kg^{-1} charcoal C had been added into the 0–1 cm layer from the

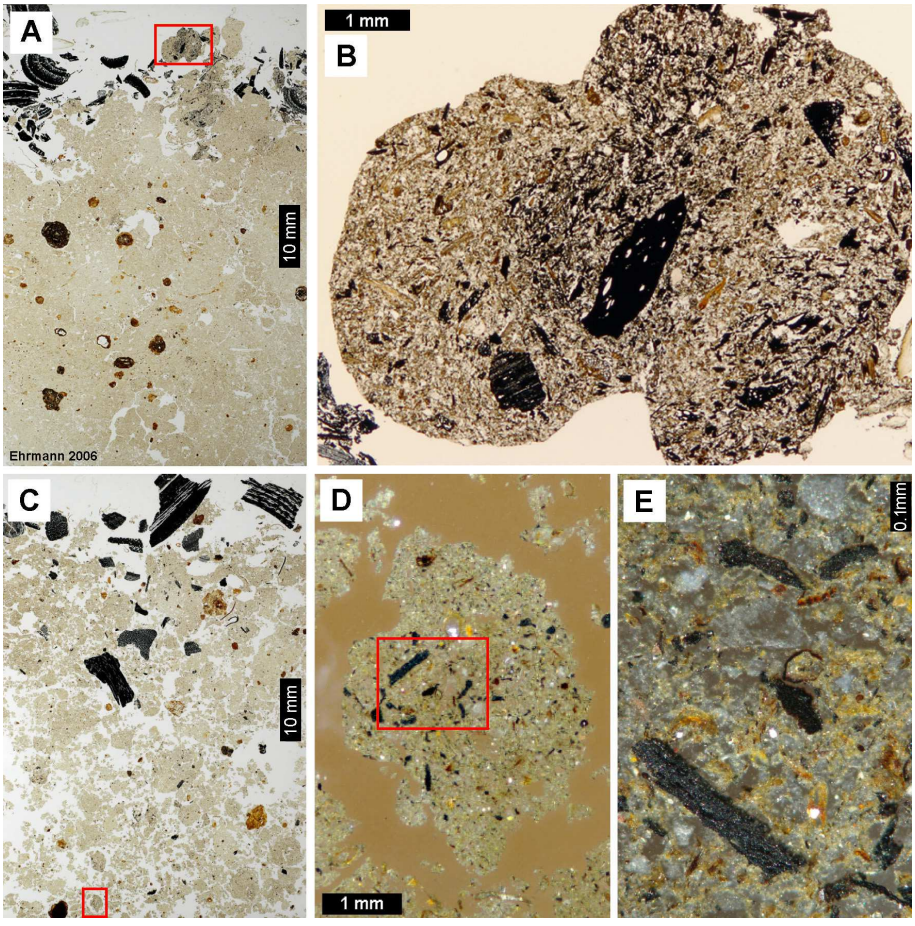

Fig. 1. Thin-sections taken from burnt plots at the Forchtenberg experimental site nearby the plot investigated in this study. **(A)** top 80 mm of a soil (burnt October 2003), showing the situation two years after burning; black charcoal particles lying on the forest floor and earthworm facies containing charcoal; the brown particles in the grey soil matrix are concretions of iron. **(B)** enlargement of the rectangle in (A) (earthworm facies). **(C)** top 80 mm of a soil (burnt October 1998), showing the situation six years after burning; charcoal particles were incorporated into the soil and translocated; **(D–E)** enlargements of the rectangles in the previous figures (earthworm facies), (E) was rotated in 90°; photographs (A–C) were taken using plain polarized light, (D) and (E) using incident light.

charcoal laid upon the surface. One year after the experimental burning, charcoal C concentrations in the 0–1 cm depth had increased by 0.4 g kg^{-1}. On the other hand, the charcoal C concentrations decreased in the 2.5–5 cm depth interval, which gave a constant charcoal C concentration throughout the top 5 cm of the soil profile (weighted average). The control samples contained charcoal, which indicated that charcoal from previous fires laid in the areas surrounding the research field already had already been mixed into the soil material.

The slash-and-burn experiment also provided data on the charcoal budget of slash-and-burn in a temperate deciduous forest. The percentage of the biomass converted to charcoal C is 8.1%, that is 5200 kg ha^{-1} left on the forest floor (Eckmeier et al., 2007). The incorporation of charcoal particles into the soil and their subsequent translocation was observed in thin-sections taken from different burning plots at the same experimental site. Mice had probably mixed charcoal particles lying on the forest floor with the uppermost part of the soil. Figure 1 indicates that earthworms had ingested charcoal particles <2 mm and distributed them in the soil profile. Figure 1a–b shows small charcoal particles incorporated into earthworm faecies lying on the soil surface. In samples taken 6.5 years after the fire (Fig. 1c–e) small charcoal particles in earthworm faecies were concentrated at a depth of 8 cm. Supporting evidence for the translocation of charcoal by soil fauna was provided by Topoliantz and Ponge (2003) and Topoliantz et al. (2006), who reported, for tropical slash-and-burn sites, that earthworms (*Pontoscolex corethrurus*) could ingest small charcoal particles, preferably mixed with humus, and who suggested a rapid incorporation of charcoal into the soil through earthworms. Thus, the increase in charcoal C in the 0–1 cm layer could be explained by mixing the charcoal particles in the litter layer with soil material, and the

decrease in the 2.5–5 cm layer by a translocation of charcoal into soil depths >5 cm. The inclusion of charcoal into soil aggregates would physically protect the charcoal from microbial decomposition (Skjemstad et al., 1996; Baldock and Smernik, 2002; Brodowski et al., 2006), but not from translocation. However, larger particles (>2 mm) were found in soils that nevertheless had resisted decomposition over millennia even in biologically active topsoil horizons (Carcaillet, 2001).

We calculated the charcoal mass from the charcoal C concentration (see Table 2). When normalized to a depth of 0–5 cm, the charcoal mass reached 1300 mg kg^{-1} after one year. Few studies report the masses of soil charcoal and if they do, the masses are often derived from different profile depths. For example, Carnelli et al. (2004) found much less charcoal (up to 19.35 mg kg^{-1}) in an alpine Podzol (10–30 cm depth), or an average of 6.18 mg kg^{-1} in soils below 2400 m a.s.l. Carcaillet and Talon (2001) reported charcoal masses of 102–863 mg kg^{-1} (800–1280 kg ha^{-1}) in soils under temperate *Fagus-Abies* forests. The comparison of charcoal C concentrations to studies that investigated the black carbon content of soils is difficult, in consideration of the methodological differences (Schmidt et al., 2001). Ansley et al. (2006) reported no change in soil black carbon concentrations even after three fires, whereas Czimczik et al. (2003) found that black carbon concentrations in soils could increase after fire by up to 40%. In this study, charcoal C increased by 21% in 0–1 cm depth one year after the fire.

3.2 Influence of burning on soil organic carbon concentrations

Soil organic carbon concentrations decreased with soil depth (p=0.000–0.002) in the three sample sets, with mean values between 53.9±1.9 (control) and 55.2±1.1 (b 1 yr) g kg^{-1} in 0–1 cm, and 31.0±1.1 (control) and 26.8±0.7 (b 1 yr) g kg^{-1} in 2.5–5 cm depth (Table 2). Compared to the control, SOC concentrations did not significantly increase, neither directly after the burning nor after one year. The SOC concentration increased after the fire (1.3 g kg^{-1} in 0–1 cm depth), but at the same time decreased in 2.5–5 cm depth, as did the charcoal C concentration. Only a small proportion of the increased SOC concentration could be contributed to charcoal C (8.7%). The proportion of charcoal C to SOC increased from 2.8% to 3.4% in one year for 0–1 cm, but did not change when normalized to 0–5 cm.

3.3 Changes in soil lightness

The soil was darkest in 0–1 cm depth (Table 2), where it became darker not only directly after the burning but significantly within one year (p=0.009). For all depths and treatments, SOC, charcoal C concentrations and the soil lightness correlated well, the correlation being strongest between SOC concentrations and L* after one year (r=−0.94**). The correlation between soil lightness and charcoal C is exponential (Fig. 2), which can be explained by the fact that the dark charcoal particles cover the surfaces of the mineral particles.

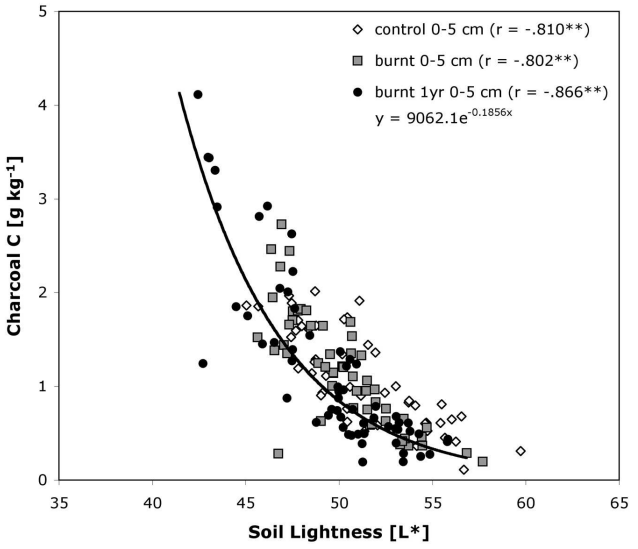

Fig. 2. The values for charcoal C concentration and soil lightness in samples from all investigated soil depths (0–5 cm) show significant and high correlations. The trendline and the equation are given for the sample set burnt 1 yr.

A significant relationship between soil colour and SOC concentrations has been already described by Schulze et al. (1993) and Konen et al. (2003). Spielvogel et al. (2004) observed that the aromatic C is mainly responsible for a dark soil colour, i.e. aryl C and L* correlated significantly (r=−0.87). These results are consistent with observations by Topoliantz et al. (2006), who reported an increase in dark humus material in topsoils after slash-and-burn together with a decrease in visible charcoal in the same material.

4 Conclusions

We investigated the effects of experimental slash-and-burn in a temperate mixed deciduous forest on soil organic and charcoal carbon and soil lightness. The main results of this study are: (i) after one year only a few charcoal particles from the forest floor had been incorporated into the soil matrix by soil mixing animals such as mice and earthworms; the proportion of charcoal C to SOC concentrations increased from 2.8 to 3.4% at 0–1 cm depth. (ii) The SOC concentrations did not show any significant differences. (iii) Soil lightness significantly decreased in the topmost soil layer and correlated with charcoal C (r=−0.87**) and to the SOC concentrations (r=−0.94**) in samples from the 0–5 cm layer.

Our results imply that, one year after the fire, only small changes in soil charcoal carbon concentrations are detectable but a certain amount of charcoal is incorporated into the soil

matrix and, over a longer time-scale, the amount of charcoal carbon stored in soils would increase.

Since little is known about prehistoric slash-and-burn techniques or burning conditions and because recent soil conditions might differ from those of several thousand years ago, implications for prehistoric times should be drawn carefully. Holocene fires in temperate deciduous forests (most were anthropogenic) could have increased soil charcoal storage, which affects pedogenesis and soil colour. Future research should combine the results of the field experiments with archaeological and palaeobotanical evidence to investigate the spatial and chronological dimensions of (pre-)historic slash-and-burn and its effects on soil properties.

Acknowledgements. We thank the experimental burning team members and supporting staff for their assistance in the field, notably Reiner Lubberich. Thanks to Ivan Woodhatch and two anonymous reviewers for their constructive comments that helped to improve the manuscript. Financial support from the University of Zurich, Switzerland, is gratefully appreciated.

Edited by: Y. Prairie

References

Anderson, M. K.: Prehistoric anthropogenic wildland burning by hunter-gatherer societies in the temperate regions: A net source, sink, or neutral to the global carbon budget?, Chemosphere, 29, 913–934, 1994.

Ansley, R. J., Boutton, T. W., and Skjemstad, J. O.: Soil organic carbon and black carbon storage and dynamics under different fire regimes in temperate mixed-grass savanna, Global Biogeochem. Cy., 20, GB3006, doi:10.1029/2005GB002670, 2006.

Baldock, J. A. and Smernik, R. J.: Chemical composition and bioavailability of thermally altered Pinus resinosa (Red pine) wood, Org. Geochem., 33, 1093–1109, 2002.

Bird, M. I., Veenendaal, E. M., Moyo, C., Lloyd, J., and Frost, P.: Effect of fire and soil texture on soil carbon in a sub-humid savanna (Matopas, Zimbawe), Geoderma, 94, 71–90, 2000.

Brodowski, S., John, B., Flessa, H., and Amelung, W.: Aggregate-occluded black carbon in soil, Eur. J. Soil Sci., 57, 539–546, 2006.

Carcaillet, C.: Are Holocene wood-charcoal fragments stratified in alpine and subalpine soils? Evidence from the Alps based on AMS ^{14}C dates, Holocene, 11, 231–242, 2001.

Carcaillet, C., Almquist, H., Asnong, H., Bradshaw, R. H. W., Carrión, J. S., Gaillard, M. J., Gajewski, K., Haas, J. N., Haberle, S. G., Hadorn, P., Müller, S. D., Richard, P. J. H., Richoz, I., Rösch, M., Sánchez Goñi, M. F. S., von Stedingk, H., Stevenson, A. C., Talon, B., Tardy, C., Tinner, W., Tryterud, E., Wick, L., and Willis, K.J.: Holocene biomass burning and global dynamics of the carbon cycle, Chemosphere, 49, 845–863, 2002.

Carcaillet, C., Richard, P. J. H., Asnong, H., Capece, L., and Bergeron, Y.: Fire and soil erosion history in East Canadian boreal and temperate forests, Quaternary Sci. Rev., 25, 1489–1500, 2006.

Carcaillet, C. and Talon, B.: Soil carbon sequestration by Holocene fires inferred from soil charcoal in the dry French Alps, Arct. Antarct. Alp. Res., 33, 282–288, 2001.

Carnelli, A. L., Theurillat, J. P., Thinon, M., Vadi, G., and Talon, B.: Past uppermost tree limit in the Central European Alps (Switzerland) based on soil and soil charcoal, Holocene, 14, 393–405, 2004.

Clark, J. S., Merkt, J., and Müller, H.: Post-Glacial Fire, Vegetation, and Human History on the Northern Alpine Forelands, South-Western Germany, J. Ecol., 77, 897–925, 1989.

Conedera, M., Krebs, P., Tinner, W., Pradella, M., and Torriani, D.: The cultivation of Castanea sativa (Mill.) in Europe, from its origin to its diffusion on a continental scale, Veg. Hist. Archaeobot., 13, 161–179, 2004.

Czimczik, C. I., Preston, C. M., Schmidt, M. W. I., and Schulze, E. D.: How surface fire in Siberian Scots pine forests affects soil organic carbon in the forest floor: Stocks, molecular structure, and conversion to black carbon (charcoal), Global Biogeochem. Cy., 17, GB1020, doi:10.1029/2002GB001956, 2003.

Dai, X., Boutton, T. W., Glaser, B., Ansley, R. J., and Zech, W.: Black carbon in a temperate mixed-grass savanna, Soil Biol. Biochem., 37, 1879–1881, 2005.

Eckmeier, E., Rösch, M., Ehrmann, O., Schmidt, M. W. I., Schier, W., and Gerlach, R.: Conversion of biomass to charcoal and the carbon mass balance from a slash-and-burn experiment in a temperate deciduous forest, The Holocene, in press, 2007.

Forbes, M. S., Raison, R. J., and Skjemstad, J. O.: Formation, transformation and transport of black carbon (charcoal) in terrestrial and aquatic ecosystems, Sci. Total Environ., 370, 190–206, 2006.

Gerlach, R., Baumewerd-Schmidt, H., van den Borg, K., Eckmeier, E., and Schmidt, M. W. I.: Prehistoric alteration of soil in the Lower Rhine Basin, Northwest Germany-archaeological, ^{14}C and geochemical evidence, Geoderma, 136, 38–50, 2006.

Gobet, E., Tinner, W., Hochuli, P. A., van Leeuwen, J. F. N., and Ammann, B.: Middle to Late Holocene vegetation history of the Upper Engadine (Swiss Alps): the role of man and fire, Veg. Hist. Archaeobot., 12, 143–163, 2003.

Goldammer, J. G., Montag, S., and Page, H.: Nutzung des Feuers in mittel- und nordeuropäischen Landschaften. Geschichte, Methoden, Probleme, Perspektiven, NNA-Berichte 10, Schneverdingen, 1997.

Hamer, U., Marschner, B., Brodowski, S., and Amelung, W.: Interactive priming of black carbon and glucose mineralisation, Org. Geochem., 35, 823–830, 2004.

Harden, J. W., Trumbore, S. E., Stocks, B. J., Hirsch, A., Gower, S. T., O'Neill, K. P., and Kasischke, E. S.: The role of fire in the boreal carbon budget, Glob. Change Biol., 6, 174–184, 2000.

Hockaday, W. C., Grannas, A. M., Kim, S., and Hatcher, P. G.: Direct molecular evidence for the degradation and mobility of black carbon in soils from ultrahigh-resolution mass spectral analysis of dissolved organic matter from a fire-impacted forest soil, Org. Geochem., 37, 501–510, 2006.

Iversen, J.: Landnam i Danmarks Stenalder. En pollenanalytisk Undersøgelse over det første Landbrugs Indvirkning paa Vegetationsudviklingen, (Land occupation in Denmark's Stone Age. A Pollen-Analytical Study of the Influence of Farmer Culture on the Vegetational Development), Danmarks Geologiske Undersølgelse, Raekke II, 66, København, 1941.

Janik, L. J., Skjemstad, J. O., Shepherd, K. D., and Spouncer, L. R.:

The prediction of soil carbon fractions using mid-infrared-partial least square analysis, Aust. J. Soil Res., 45, 73–81, 2007.

Kalis, A. J., Merkt, J., and Wunderlich, J.: Environmental changes during the Holocene climatic optimum in central Europe – human impact and natural causes, Quaternary Sci. Rev., 22, 33–79, 2003.

Kalis, A. J. and Meurers-Balke, J.: Die „Landnam"-Modelle von Iversen und Troels-Smith zur Neolithisierung des westlichen Ostseegebietes – ein Versuch ihrer Aktualisierung, Prähistorische Zeitschrift, 73, 1–24, 1998.

Konen, M. E., Burras, C. L., and Sandor, J. A.: Organic Carbon, Texture, and Quantitative Color Measurement Relationships for Cultivated Soils in North Central Iowa, Soil Sci. Soc. Am. J., 67, 1823–1830, 2003.

Kuhlbusch, T. A. J.: Black carbon and the carbon cycle, Science, 280, 1903–1904, 1998.

Lüning, J.: Steinzeitliche Bauern in Deutschland: die Landwirtschaft im Neolithikum. Universitätsforschungen zur prähistorischen Archäologie, 58, Bonn, 2000.

Ojima, D. S., Schimel, D. S., Parton, W. J., and Owensby, C. E.: Long-Term and Short-Term Effects of Fire on Nitrogen Cycling in Tallgrass Prairie, Biogeochemistry, 24, 67–84, 1994.

Patterson III, W. A., Edwards, K. J., and Maguire, D. J.: Microscopic charcoal as a fossil indicator of fire, Quaternary Sci. Rev., 6, 3–23, 1987.

Preston, C. M. and Schmidt, M. W. I.: Black (pyrogenic) carbon: a synthesis of current knowledge and uncertainties with special consideration of boreal regions, Biogeosciences, 3, 397–420, 2006,
http://www.biogeosciences.net/3/397/2006/.

Pyne, S. J.: Maintaining focus: An introduction to anthropogenic fire, Chemosphere, 29, 889–911, 1994.

Roscoe, R., Buurman, P., Velthorst, E., and Pereira, J.: Effects of fire on soil organic matter in a "cerrado sensu-stricto" from Southeast Brazil as revealde by changes in δ^{13} C, Geoderma, 95, 141–160, 2000.

Rösch, M.: Prehistoric land use as recorded in a lake-shore core at Lake Constance, Veg. Hist. Archeobot., 2, 213–232, 1993.

Rösch, M.: Anthropogener Landschaftswandel in Mitteleuropa während des Neolithikums – Beobachtungen und Überlegungen zum Verlauf und möglichen Ursachen, Germania, 78, 293–318, 2000.

Rösch, M., Ehrmann, O., Herrmann, L., Schulz, E., Bogenrieder, A., Goldammer, J. P., Hall, M., Page, H., and Schier, W.: An experimental approach to Neolithic shifting cultivation, Veg. Hist. Archaeobot., 11, 143–154, 2002.

Schmidt, M. W. I., Skjemstad, J. O., Czimczik, C. I., Glaser, B., Prentice, K. M., Gelinas, Y., and Kuhlbusch, T. A. J.: Comparative analysis of black carbon in soils, Global Biogeochem. Cy., 15, 163–167, 2001.

Schmidt, M. W. I., Skjemstad, J. O., and Jäger, C.: Carbon isotope geochemistry and nanomorphology of soil black carbon: Black chernozemic soils in central Europe originate from ancient biomass burning, Global Biogeochem. Cy., 16, GB1123, doi:10.1029/2002GB001939, 2002.

Schulze, D. G., Nagel, J. L., Van Scoyoc, G. E., Henderson, T. L., Baumgardner, M. F., and Stott, D. E.: Significance of soil organic matter in determining soil colors, in: Soil Color, edited by: Bigahm, J. M. and Ciolkosz, E. J., 71–90, 1993.

Skjemstad, J. O., Clarke, P., Taylor, J. A., Oades, J. M., and McClure, S. G.: The Chemistry and Nature of Protected Carbon in Soil, Aust. J. Soil Res., 34, 251–271, 1996.

Skjemstad, J. O., Spouncer, L. R., Cowie, B., and Swift, R. S.: Calibration of the Rothamsted organic carbon turnover model (RothC ver. 26.3), using measurable soil organic carbon pools, Aust. J. Soil Res., 42, 79–88, 2004.

Spielvogel, S., Knicker, H., and Kögel-Knabner, I.: Soil organic matter composition and soil lightness, J. Plant Nutr. Soil Sci., 167, 545-555, 2004.

Stoops, G.: Guidelines for analysis and description of soil and regolith thin sections, Madison, Wisconsin, 2003.

Tinner, W., Conedera, M., Ammann, B., and Lotter, A. F.: Fire ecology north and south of the Alps since the last ice age, Holocene, 15, 1214–1226, 2005.

Topoliantz, S. and Ponge, J. F.: Burrowing activity of the geophagous earthworm Pontoscolex corethrurus (Oligochaeta: Glossoscolecidae) in the presence of charcoal, Appl. Soil Ecol., 23, 267–271, 2003.

Topoliantz, S., Ponge, J. F., and Lavelle, P.: Humus components and biogenic structures under tropical slash-and-burn, Eur. J. Soil Sci., 57, 269-278, 2006.

Torrent, J. and Barrón, V.: Laboratory Measurement of Soil Color: Theory and Practice, in: Soil Color, edited by: Bigahm, J. M. and Ciolkosz, E. J., 21–33, 1993.

van der Werf, G. R., Randerson, J. T., Giglio, L., Collatz, G. J., Kasibhatla, P. S., and Arellano, A. F.: Interannual variability in global biomass burning emissions from 1997 to 2004, Atmos. Chem. Phys., 6, 3423–3441, 2006,
http://www.atmos-chem-phys.net/6/3423/2006/.

Viscarra Rossel, R. A., Walvoort, D. J. J., McBratney, A. B., Janik, L. J., and Skjemstad, J. O.: Visible, near infrared, mid infrared or combined diffuse reflectance spectroscopy for simultaneous assessment of various soil properties, Geoderma, 131, 59–75, 2006.

Wang, X., Peng, P. A., and Ding, Z. L.: Black carbon records in Chinese Loess Plateau over the last two glacial cycles and implications for paleofires, Palaeogeography, Palaeoclimatology, Palaeoecology, 223, 9–19, 2005.

Willis, K. J. and van Andel, T. H.: Trees or no trees? The environments of central and eastern Europe during the Last Glaciation, Quaternary Sci. Rev., 23, 2369–2387, 2004.