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Only small changes in soil organic carbon and charcoal concentrations found one year after experimental slash-and-burn in a temperate deciduous forest

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, Winterthurerstr. 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

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

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. In a long-term experimental burning site, we investigated the effects of slash-and-burn and determined soil organic carbon, charcoal carbon and nitrogen concentrations and 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 after burning. The main results are that (i) only few charcoal particles from the forest floor were incorporated into the soil matrix by soil mixing animals. In 0–1 cm and during one year, the charcoal C concentrations increased only by 0.4 g kg^{-1} and the proportion of charcoal C to SOC concentrations increased from 2.8 to 3.4%; (ii) the SOC concentrations did not show any significant differences; (iii) soil lightness significantly decreased in the topmost soil layer and correlated with the concentrations of charcoal C (r=-0.87**) and SOC (r=−0.94**) in samples 0–5 cm. We concluded that the soil colour depends on the proportion of aromatic charcoal carbon in total organic matter and that Holocene burning could have influenced soil charcoal concentrations and soil colour.

1 Introduction

Anthropogenic burning was common in the past and probably has been used as a tool for hunting, herding and farming with high spatial and temporal variation, documented in charcoal records revealed also for Central European deciduous forests. 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

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may have affected the global carbon cycle during the last 10 000 years (e.g. Anderson, 1994; Pyne, 1994; Carcaillet et al., 2002; Tinner et al., 2005). Progressing climate change leads to warmer and drier summers, and an increase in wildfires in temperate regions and deciduous forests (Westerling et al., 2006).

Biomass burning releases an estimated 2.5 Pg atmospheric carbon per year (van der Werf et al., 2006) and produces a substantial amount of charcoal. A main component of charcoal is black carbon, which is part of a continuum of material produced during incomplete combustion of biomass (Kuhlbusch, 1998). Although recent investigations showed that microbes can degrade black carbon (Hamer et al., 2004; Hockaday et al., 2006), it 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 show different trends: either no changes in soil organic carbon stocks (Dai et al., 2005; Roscoe et al., 2000), a reduction (Bird et al., 2000), or an increase (Ojima et al., 1994). However, data considering soil carbon and charcoal carbon stocks and their dynamics in the soil profile after fire is limited, and to our knowledge no quantitative assessment for fires in temperate deciduous forests has yet been attempted (Preston and Schmidt, 2006).

Burning could also affect 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 accountable for the dark colour of Chernozem humus horizons (Schmidt et al., 2002). One-third of the organic matter of fossil dark soil horizons embedded in lighter Haplic Luvisols consisted of black carbon that derived from Holocene anthropogenic burning (Gerlach et al., 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 to reconstruct environmental history and past forest-fires (e.g. 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 fire, or charcoal burial and mixing within the soil profile.

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 that was 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. The 3.5 ha large area is situated in a temperate deciduous forest dominated by *Fagus, Acer* and *Carpinus* (Rösch et al., 2002). The area has been forested for at least two centuries; the trees are about 40 years old. The soil is a slightly acidic Haplic Luvisol (WRB-FAO) with partly stagnic properties (Table 1). We investigated the changes in soil organic carbon, nitrogen and charcoal carbon of the topsoil material (Ah, 0–16 cm depth), which is followed by an eluviation horizon (E), an argic horizon with hydromor-

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phic features (Bt), a cambic to argic horizon (Bvt) and 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 small wood pieces were allowed to dry one summer. In autumn (October 2004), an area of 11×8 m was burnt. Small wood pieces were collected in a row and ignited, and the pile of burning wood was drawn over the ground using long hooks for pulling and was permanently fed with wood. 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 loggers. The maximum temperature measured was 72°C at 1 cm depth.

2.2 Soil sampling and analyses

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

Total carbon and nitrogen 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 bicarbonates.

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 grinded and directly measured, and the

obtained spectra 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 reaches 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 the grinding of 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 7.5×5.5×0.03 cm 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

The bulk density increased from an average 0.61±0.9 (standard error) g cm^{-3} before burning to 0.77±0.5 g cm^{-3} after one year (0–1 cm), which made it difficult to compare carbon stocks for the different sample sets. Therefore, we report only the charcoal C and SOC concentrations.

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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) (Table 2, Fig. 1). One year after the experimental burning, charcoal C concentrations increased in 0–1 cm depth by 0.4 g kg^{-1}; immediately after the burning 0.1 g kg^{-1} charcoal C had been added. On the other hand, the charcoal C concentrations decreased in 2.5–5 cm depth, which leads to a constant charcoal C concentration for the total depth of 0–5 cm; both control samples and samples taken after one year contained 1.0 g kg^{-1} charcoal C (weighted average for 0–5 cm depth). The fact that the control samples contained charcoal indicated that charcoal produced during previous fires in the surrounding of the research field already had been mixed into the soil material.

Our slash-and-burn experiment also provided data on the charcoal budget of slash-and-burn in a temperate deciduous forest; it left 5200 kg ha^{-1} charcoal C on the forest floor (Eckmeier et al., 2007). We calculated charcoal C stocks of 120 kg ha^{-1} in 0–5 cm soil depth one year after burning. The stocks are not comparable inbetween the sample sets due to high bulk densities variations, but they indicate that after one year only 2.3% of the macrocharcoal on the soil surface was stored in 0–5 cm.

The incorporation of charcoal particles and their subsequent translocation was observed in thin-sections taken at the same experimental site on different burning plots. Mice probably mixed charcoal particles lying on the forest floor with the uppermost part of the soil, and Fig. 2 shows that earthworms ingested charcoal particles <2 mm and distributed them in the soil profile. In samples taken 6.5 years after a fire (Figs. 2c–e) small charcoal particles in earthworm facies were found in a depth of 8 cm. Figures 2a–b show small charcoal particles incorporated into earthworm facies lying on the soil surface. Supporting evidence for translocation of charcoal by soil fauna was provided by Topoliantz and Ponge (2003) and Topoliantz et al. (2006), who showed for tropical slash-and-burn sites that earthworms (*Pontoscolex corethrurus*) could ingest small charcoal particles, preferably mixed with humus, and who suggested a rapid

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incorporation of charcoal into the soil through earthworms. Thus, the increase in charcoal C in 0–1 cm could be explained by mixing the charcoal particles in the litter layer with soil material, and the decrease in 2.5–5 cm 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, also larger particles (>2 mm) were found in soils that nevertheless resisted decomposition over millennia even in biological active topsoil horizons (Carcaillet, 2001).

We calculated the charcoal mass from the charcoal C content (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, e.g. 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. However, the comparison of the soil charcoal data reported here is difficult because we did not investigate the whole soil profile. Also the comparison of charcoal C concentrations to studies that investigated the black carbon content of soils is difficult, considering 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 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 samples 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, Fig. 1). 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 concentrations. 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, Fig. 1), and became even darker directly after the burning ($p=0.028$) and within one year ($p=0.009$). For all depths and treatments, SOC, charcoal C concentrations and the soil lightness correlated significantly, the correlation being strongest between SOC concentrations and L* after one year ($r=-0.94^{**}$). The fact that the correlation between soil lightness and charcoal C is exponential (Fig. 3) could be explained by the fact that the dark charcoal particles cover the surfaces of the mineral particles. Darkening of a soil could be the result of higher proportions of aromatic C in the total soil organic carbon.

A significant relationship between soil colour and SOC concentrations was 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 previous observations by Topoliantz et al. (2006), who registered an increase in dark humus material in topsoils after slash-and-burn together with a decrease in visible charcoal in the same material. In Australia (Skjemstad et al., 1996) and South America (Glaser et al., 2002) it was shown that fire management practice and charcoal inputs could form black soils. Black soils like Chernozems could contain high proportions of charred organic matter, although the reported amounts depend on the method used to detect it (Schmidt et al., 2001, 2002).

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3.4 Implications for past fires and environments

Recent soil conditions might differ from those several thousand years ago, and implications for prehistoric times should be drawn carefully. Late Neolithic slash-and-burn (4400–2200 BC) was used to prepare the fields in the vicinity of the settlements. In Central Europe, Neolithic settlements were found mainly in the loess covered areas, but with the onset of the Late Neolithic also soils that are less favourable for agriculture were colonised (Rösch, 1993; Kalis and Meurers-Balke, 1998; Lüning, 2000). Slash-and-burn appeared with this extension of settlement area, and the release of nutrients during burning may have been a prerequisite for planting crops on these poor soils (W. Schier, personal communication). Because the positive effects of vegetation fire on crop growing last only one year, the burning had to be repeated annually in newly cleared areas. This prevents re-oxidation of charcoal carbon through a subsequent fire, as was shown for regions with higher fire frequency (Czimczik et al., 2005).

4 Conclusions

We investigated the effects of experimental biomass burning (slash-and-burn) in a temperate mixed deciduous forest on soil organic and charcoal carbon and soil lightness one year after the fire. The main results of this study are: (i) after one year only few charcoal particles from the forest floor were 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% in 0–1 cm. (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 SOC concentrations ($r=-0.94^{**}$) in samples 0–5 cm. We concluded that the soil colour depends on the proportion of aromatic charcoal carbon in total organic matter.

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

a longer time-scale the amount of charcoal carbon stored in soils would increase. Thus, Holocene fires in temperate deciduous forests, which were mainly anthropogenic fires, could have increased soil charcoal storage, which affected pedogenesis and soil colour. Future research should combine the results of field experiments and archaeological and palaeobotanical evidence to investigate the spatial and chronological dimensions of (pre)historic slash-and-burn and its effects on soil properties.

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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. Cycles, 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, Organic Geochemistry, 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, European 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., Carrion, 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., Sanchez 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, Quat. 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, Arctic, Antarctic and Alpine Research, 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.
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. Cycles, 17, 1020, doi:10.1029/2002BG001956, 2003.
Czimczik, C. I., Schmidt, M. W. I., and Schulze, E. D.: Effects of increasing fire frequency on black carbon and organic matter in Podzols of Siberian Scots pine forests, European J. Soil Sci., 56, 417–428, 2005.
Dai, X., Boutton, T. W., Glaser, B., Ansley, R. J., and Zech, W.: Black carbon in a temperate mixed-grass savanna, Soil Biology & Biochemistry, 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 experimental slash-and-burn in a temperate deciduous forest, 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. Tot. 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.
Glaser, B., Lehmann, J., and Zech, W.: Ameliorating physical and chemical properties of highly weathered soils in the tropics with charcoal – a review, Biology and Fertility of Soils, 35, 219–230, 2002.
Hamer, U., Marschner, B., Brodowski, S., and Amelung, W.: Interactive priming of black carbon and glucose mineralisation, Organic Geochemistry, 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, Global Change Biology, 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, Organic Geochemistry, 37, 501–510, 2006.
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, Australian J. Soil Res., 45, in press, 2007.
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, Quat. 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, Vegetation History and Archeobotany, 2, 213–232, 1993.
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, Vegetation History and Archaeobotany, 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. Cycles, 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. Cycles, 16, 1123, 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., Soil Sci. Soc. Am., 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, Journal of Plant Nutrition and Soil Science, 167, 545–555, 2004.
Stoops, G.: Guidelines for analysis and description of soil and regolith thin sections, Soil Sci. Soc. Am., 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 Ecology, 23, 267–271, 2003.
Topoliantz, S., Ponge, J. F., and Lavelle, P.: Humus components and biogenic structures under tropical slash-and-burn, European 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: Bigham, J. M. and Ciolkosz, E. J., Soil Sci. Soc. Am., 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.
Westerling, A. L., Hidalgo, H. G., Cayan, D. R., and Swetnam, T. W.: Warming and Earlier Spring Increase Western U.S. Forest Wildfire Activity, Science, 313, 940–943, 2006.
Willis, K. J. and van Andel, T. H.: Trees or no trees? The environments of central and eastern Europe during the Last Glaciation, Quat. Sci. Rev., 23, 2369–2387, 2004.
Zackrisson, O., Nilsson, M. C., and Wardle, D. A.: Key ecological function of charcoal from wildfire in the Boreal forest, Oikos, 77, 10–19, 1996.

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

Horizon	Depth cm	Sand	Silt	Clay	pH $CaCl_2$	C/N
		— $g\,kg^{-1}$ —				
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

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.

Sample		n	L*	SOC	N	C/N	Charcoal C	Charcoal C	Charcoal mass [1]
	cm			— g kg^{-1} —			g kg^{-1}	% of SOC	g kg^{-1}
control	0–1	14	49.5±0.5	53.9±1.9	4.0±0.1	13	1.5±0.1	2.8	2.0
control	1–2.5	14	51.3±0.4	38.9±1.7	3.1±0.1	13	1.1±0.1	2.7	1.4
control	2.5–5	19	52.7±0.4	31.0±1.1	2.5±0.1	12	0.8±0.0	2.5	1.0
average[2]	0–5		51.6	37.9	3.0	13	1.0	2.6	1.3
burnt	0–1	17	47.9±0.2	55.2±1.7	5.5±0.6	12	1.6±0.1	3.0	2.1
burnt	1–2.5	17	50.3±0.3	39.5±1.2	4.1±0.4	11	1.1±0.1	2.8	1.4
burnt	2.5–5	19	52.5±0.3	29.7±1.1	4.1±0.7	11	0.8±0.1	2.6	1.0
average[2]	0–5		50.9	37.7	4.4	11	1.1	2.7	1.4
burnt 1yr	0–1	20	46.3±0.3	55.2±1.1	3.8±0.1	15	1.9±0.1	3.4	2.5
burnt 1yr	1–2.5	20	49.6±0.3	38.8±1.0	2.9±0.1	13	1.1±0.1	2.7	1.4
burnt 1yr	2.5–5	20	53.0±0.2	26.8±0.7	2.2±0.1	12	0.6 (0.4)[3]±0.0	2.1	0.7
average[2]	0–5		50.6	36.0	2.7	13	1.0 (0.9)[3]	2.5	1.3

[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 1 yr sample set.

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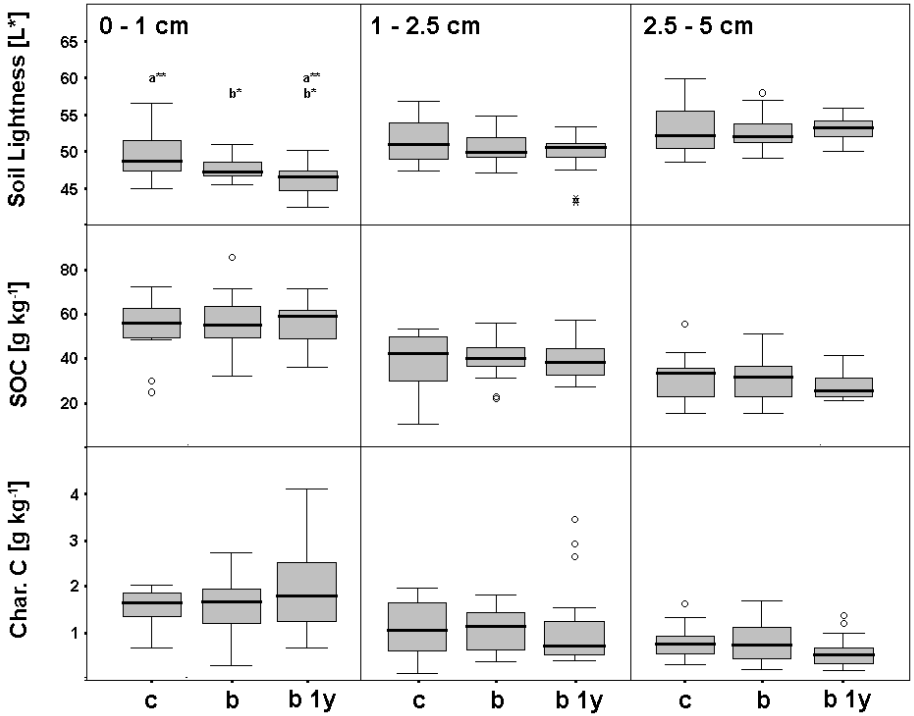

Fig. 1. Boxplots showing median, percentiles, minimum and maximum values and outliers from soil lightness, SOC and charcoal C concentrations (c=control, b=burnt, b 1 y = after one year). Same letters above the boxplot indicate a significant difference between the sample sets in the same soil depth (*=p<0.05; **=p<0.01).

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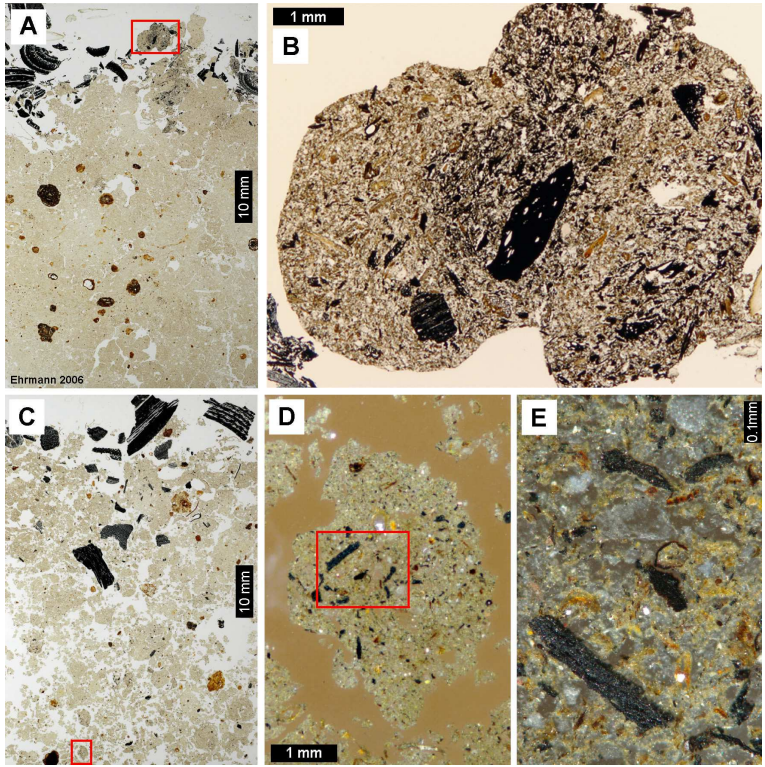

Fig. 2. Thin-sections taken from burnt plots at the Forchtenberg experimental site nearby the plot investigated in this study. **(A)** top 80 mm of a soil (burnt October 2003), showing the situation two years after burning; black charcoal particles lying on the forest floor and earthworm facies containing charcoal; the brown particles in the grey soil matrix are iron concretions. **(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.

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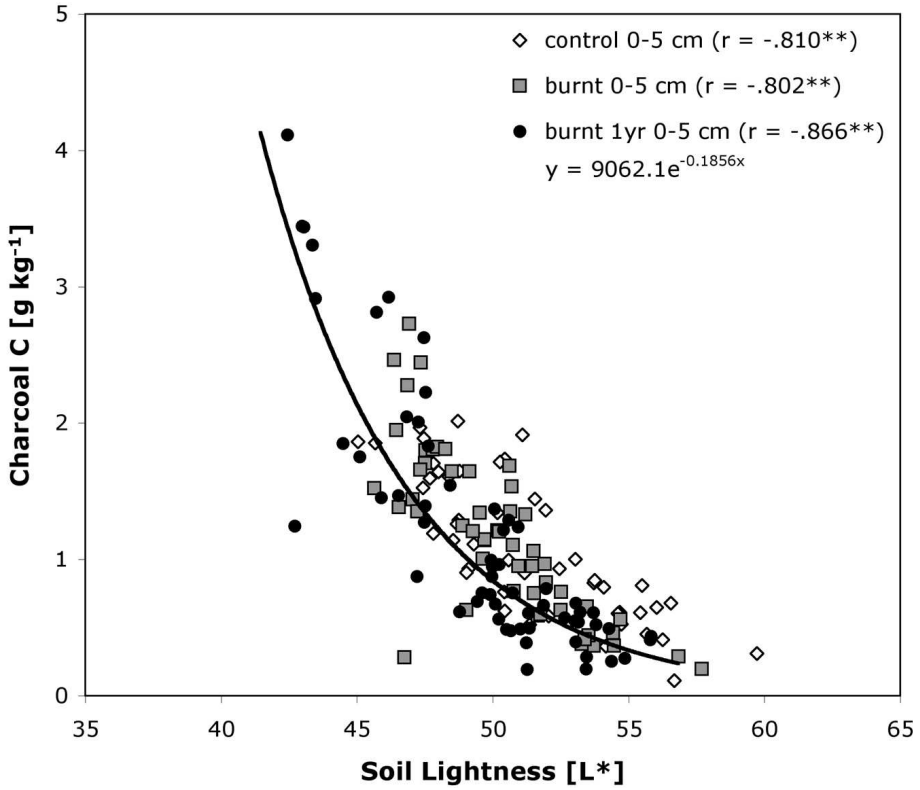

Fig. 3. The values for charcoal C concentration and soil lightness in samples from all investigated soil depths (0–5 cm) show significant and high correlations. The trendline and the equation are given for the sample set burnt 1 yr.

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