

## Consumption of residual pyrogenic carbon by wildfire

C. Santín<sup>A,B,D</sup>, S. H. Doerr<sup>A</sup>, C. Preston<sup>C</sup> and R. Bryant<sup>A</sup>

<sup>A</sup>Department of Geography, College of Science, Swansea University, Singleton Park, Swansea, SA2 8PP, UK.

<sup>B</sup>Indurot, Universidad de Oviedo, Campus Universitario de Mieres, E-33600 Mieres, Spain.

<sup>C</sup>Pacific Forestry Centre of Natural Resources Canada, 506 West Burnside Road, Victoria, BC, V8Z 1M5, Canada.

<sup>D</sup>Corresponding author. Email: c.s.nuno@swansea.ac.uk

**Abstract.** Pyrogenic carbon (PyC) produced during vegetation fires represents one of the most degradation resistant organic carbon pools and has important implications for the global carbon cycle. Its long-term fate in the environment and the processes leading to its degradation are the subject of much debate. Its consumption in subsequent fires is considered a potential major mechanism of abiotic PyC degradation; however, no quantitative data supporting this removal pathway have been published to date. To address this gap, we quantified consumption of residual PyC at the forest floor during an experimental fire, representative of a typical boreal wildfire, complemented by exploratory laboratory heating experiments. Labelled PyC (pinewood charcoal from a slash pile burn), in granular form contained in stainless steel mesh bags and as individual pieces, were placed at ~2-cm depth within the forest floor. The median mass loss of granular charcoal was 6.6%, with 75% of the samples losing <15%, and of individual pieces 15.1% with 75% of the samples losing <25%. The mass losses under laboratory conditions, although somewhat higher than in the field, confirm an overall low consumption of PyC. The limited losses of PyC found here do not support the widely held notion that wildfire is a major cause of loss for residual PyC.

**Additional keywords:** biochar, black carbon, boreal, charcoal, combustion, forest floor, soil.

Received 15 November 2012, accepted 25 April 2013, published online 13 August 2013

### Introduction

Pyrogenic carbon (PyC, also known as black carbon) is formed during incomplete combustion of organic fuels and comprises a continuum of pyrogenic organic compounds ranging from partly charred material through charcoal to soot (Goldberg 1985). The enhanced resilience of PyC to degradation, in comparison to its unburned organic precursors (Schmidt *et al.* 2011), is the underlying principle for the potential of PyC to act as a longer-term carbon (C) store in soils and sediments (Lehmann *et al.* 2008).

Despite its potential importance for C sequestration, some critical processes that control PyC residence times in the environment remain unquantified, leading to uncertainties in the net effects of PyC on global C dynamics. For example, to determine PyC half-life in soils, experimental work has mainly focused on biotic degradation of PyC, investigating its microbial decomposition under a range of environmental conditions (Liang *et al.* 2008; Kuzyakov *et al.* 2009; Hilscher and Knicker 2011a, 2011b; Zimmerman *et al.* 2011). Biotic degradation is indeed the dominant pathway for PyC decomposition in soils (Kuzyakov *et al.* 2009; Santos *et al.* 2012); however, under certain conditions, abiotic degradation may also be important (Cheng *et al.* 2006; Cheng and Lehmann 2009). Fire is increasingly seen as a main abiotic mechanism of PyC loss in soils (Foereid *et al.* 2011). Most ecosystems are exposed to a specific

fire recurrence interval, which can range from as short as a few years for savanna grasslands to many decades for some shrub and forest types (Malamud *et al.* 1998). Any PyC generated during a fire, and subsequently not degraded, transported off-site, or incorporated deeper into the soil, is therefore susceptible to acting as fuel and may be partially or wholly consumed in subsequent fires. Studies dealing with accumulation of PyC in soils have proposed consumption of PyC by fire as a potential major mechanism of its loss (Ohlson and Tryterud 2000; Czimeczik *et al.* 2005; Preston and Schmidt 2006; Czimeczik and Masiello 2007; Kane *et al.* 2010). Intriguingly, none of these studies present direct evidence to support this hypothesis and, to our knowledge, specific attempts at quantifying consumption of existing PyC by subsequent fires have yet to be made.

This study addresses this research gap by quantifying the consumption of known quantities of PyC (in the form of charcoal) during a boreal forest fire. The boreal forest is the largest terrestrial biome in the world and, hence, boreal C storage and sequestration is a critical component of the global C cycle (Seedre *et al.* 2011). Fire is the dominant driver of the C balance in this biome (Bond-Lamberty *et al.* 2007), with one-third of the net primary productivity being consumed by fire every year (Harden *et al.* 2000). PyC production within boreal regions (forests and peatlands) has been estimated to be ~7–17 Tg year<sup>-1</sup> with long PyC half-lives (in the range of

5000–7000 years for the most recalcitrant PyC fractions) due to the specific climate, formation and soil conditions (Preston and Schmidt 2006). As regards mechanisms and pathways of PyC losses, fire is considered to be a particularly notable driver of PyC degradation here (e.g. Preston and Schmidt 2006; Czimczik and Masiello 2007); however, direct evidence for this has not been provided to date.

To test the hypothesis that fire is an important driver for PyC loss, we took advantage of an experimental boreal ‘wildfire’ allowing pre- and post-fire sampling, as well as temperature monitoring spanning the fire and immediate post-fire period. We also explored PyC consumption under controlled laboratory conditions using the same PyC sample types, and temperature-duration profiles representative of those recorded in the field.

## Methods

### FireSmart experimental ‘wildfire’

In June 2012, an experimental fire, aimed at simulating wildfire conditions, was conducted as part of the Canadian Boreal Community FireSmart Project at Fort Providence, Northwest Territories, Canada (61°34'55"N, 117°11'55"W). This boreal region has a dry, subhumid continental climate with low annual precipitation (~300 mm) and a wildfire season generally lasting from May to September. The terrain is flat with an elevation of ~160 m AMSL and stony gravelly loam or sandy clay loam soils (Alexander *et al.* 2004). The experimental plot (70 × 70 m) was a mature stand of jack pine (*Pinus banksiana*) originating from a stand-replacement fire in 1931, with a tree density (live and dead) of ~7600 stems ha<sup>-1</sup> and average tree height of 12 m. The forest floor, composed of litter, mosses and lichens, had an average depth to the mineral soil surface of 6.4 cm (range 3.5 to 10 cm, *n* = 27). The understorey was very sparse with a few jack pine and black spruce (*Picea mariana*) saplings and shrubs.

Before the fire, three parallel transects of 18-m length were established 7.5 m apart in the direction of the prevailing wind (E-W) in the central area of the plot. These were instrumented at a spacing of 2 m with thermocouples connected to data loggers (Lascar, Easylog) to continuously (every second) record temperatures at the forest floor surface. In total, 27 points (9 per transect) were monitored.

The experimental fire was an intermittent crown fire, reproducing a typical wildfire for this region (Fig. 1a). At the time of ignition, air temperature was 28°C with winds from the ESE at 10–12 km h<sup>-1</sup>. Line ignition was initiated along the upwind east

edge of the plot using a terra torch. The average flame height was 5–6 m above canopy level and the spread rate was ~6–7 m min<sup>-1</sup>. The fire consumed part of the forest floor, with an average depth of burn of the forest floor of 2.6 cm (range 0.4 to 6.0 cm, *n* = 108), generating a continuous layer of ash of ~1.4-cm depth (range 0.5 to 3.0 cm, *n* = 108) (Fig. 1b). The overall fireline intensity of 8000 kW m<sup>-1</sup> was within the range typical of high-intensity boreal crown fires in Canada (de Groot *et al.* 2009).

### Consumption of residual PyC during the experimental ‘wildfire’

PyC samples (charcoal pieces 2–4 cm long and 1–3 cm wide) were collected from the remains of a jack pine wood pile burned the previous winter and adjacent to the experimental plot. Some charcoal pieces were kept intact for experimentation (from here on referred to as ‘PyC pieces’), and some were gently crushed and then sieved to generate homogeneous granular material with a particle size between 1 and 1.7 mm (from here on referred to as ‘granular PyC’). Samples of the latter (~1 g) were placed inside flat 5 × 5-cm bags (made of stainless steel mesh with 0.2-mm aperture) to separate our ‘pre-existing residual’ charcoal samples from any new PyC material generated by the fire.

One PyC piece (1–5 g) and one mesh bag with granular PyC were placed at ~2-cm depth within the forest floor every 2 m along the experimental transects and adjacent to the thermocouples. Both PyC pieces (*n* = 27) and mesh bags (*n* = 27) were labelled with aluminium tags to allow identification. The day after the fire, thermocouples, mesh bags and PyC pieces were recovered (Fig. 1c). All PyC samples were air-dried and weighed pre- and post-fire, and their change in mass determined. The temperature-time profiles at the adjacent thermocouples were analysed to determine the periods for which the temperature exceeded specific values and also to determine the typical maximum rates of heating at the forest floor surface.

### Consumption of PyC in exploratory laboratory experiments

The same types of PyC samples used in the field were also subjected to heating under controlled laboratory conditions. A series of specific temperatures and exposure times were chosen to reflect relevant temperature-duration conditions recorded during the experimental fire, with the lowest temperature chosen above the value where ignition might be expected to occur (300°C; Lizhong *et al.* 2008). Thus, PyC pieces (1–2 g)



**Fig. 1.** (a) The FireSmart experimental ‘wildfire’ (June 2012). Study transects were located towards the right hand side, experiencing crown fire conditions. (b) Ash layer following the burn with ‘depth of burn pin’ indicating consumption depth of the forest floor. (c) Mesh bag containing ‘granular pyrogenic carbon (PyC)’ (indicated by arrow) and a ‘PyC piece’ (indicated by finger) after the fire, just before collection.

and granular PyC (1 g, using the same mesh bags employed in the field) were placed in a pre-heated muffle furnace (Carbolite Ltd) at temperatures of 370, 470 and 570°C for exposure times of 155, 105 and 65 s. These were based on the range of conditions determined from the thermocouple data recorded in the field (see Results section and note that the experimental times were increased by 5 s compared with the field times to account for time lost while introducing the samples in the furnace). The same types of thermocouples employed in the field were used to monitor the temperatures in the furnace, both close to the PyC pieces and inside the mesh bags. Samples were dried at 105°C for 24 h and weighed before and after the experiment to eliminate any effect of differences in residual moisture content on sample weight. Tests were performed in triplicate.

### Data analysis

PyC consumption was calculated as the percentage of mass loss as follows:

$$\text{PyC loss} = \frac{(\text{Pre-fire mass} - \text{Post-fire mass})}{\text{Pre-fire mass}} \times 100$$

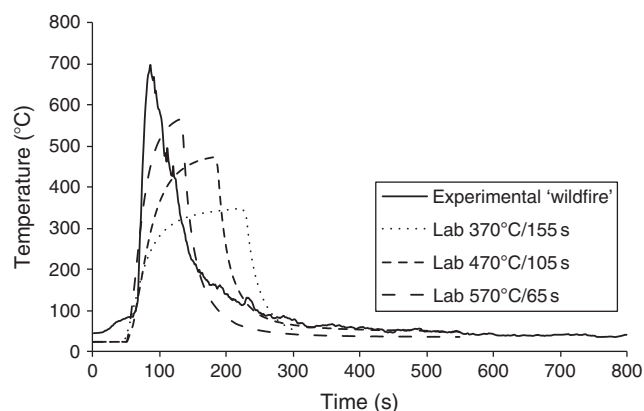
Spearman rank correlations were used to test the statistical dependence ( $P \leq 0.05$ ) between variables in the field experiment (i.e. PyC absolute and relative mass losses, depth of burn, maximum temperatures and period above various threshold temperatures), using the SPSS 20 software.

## Results

### PyC consumption during the experimental 'wildfire'

Thermocouples located at the surface of the forest floor registered maximum temperatures ranging from 550 to 976°C (average max. 747°C). Maximum heating rates were  $\sim 20$ – $50^\circ\text{C s}^{-1}$  and cooling rates were slower, ranging from  $-10$  to  $-20^\circ\text{C s}^{-1}$ . Regarding periods above specific temperatures, average durations were 150, 100 and 60 s for 370, 470 and 570°C. A typical temperature profile, recorded at 16 m west along the southern transect, is shown in Fig. 2.

The frequency distribution of the mass loss (%) arising from consumption of PyC during the fire followed a right-tailed form



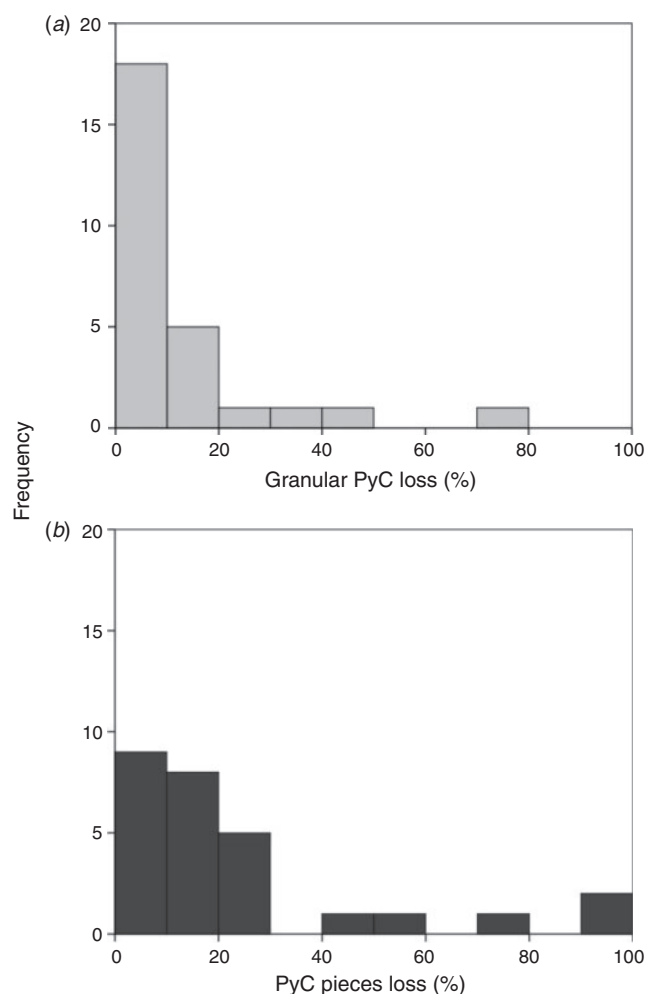
**Fig. 2.** Examples of typical temperature-time profiles recorded during the experimental fire at the forest floor surface (solid line) and during the laboratory experiments in the muffle furnace for the three tested combinations of temperature and exposure times (dashed lines).

for both PyC types (Fig. 3). The granular PyC had a median mass loss of 6.6%, with 75% of the samples losing  $<15\%$  and a maximum mass loss of 70.4% (Fig. 3a and Table 1). The PyC pieces experienced a median mass loss of 15.1% with 75% of the samples losing  $<25\%$  (Fig. 3b and Table 1). Two PyC pieces suffered total combustion (100%) whereas another two showed no loss.

No significant correlations ( $P > 0.05$ ; all correlation coefficients  $[\rho]$  were  $<0.4$ ) were found between: (i) mass losses of PyC pieces and the granular PyC placed at each sampling point (on either relative or absolute bases); (ii) mass losses of both charcoal types and the maximum temperatures reached or the period above various threshold temperatures during burning; and (iii) mass losses of both charcoal types and depth of burn at respective sampling points.

### PyC consumption under laboratory conditions

Rates of increase in temperature following insertion of PyC material into the pre-heated muffle furnace, and rates of cooling following their removal, were of a similar order to those



**Fig. 3.** Frequency distribution of sample mass loss (%) during the Fire-Smart experimental fire for (a) granular pyrogenic carbon (PyC) and (b) PyC pieces ( $n = 27$  each).

**Table 1.** Median mass loss and mass loss range, as a percentage of the initial mass (%), for granular pyrogenic carbon (PyC) and PyC pieces, following the experimental fire ( $n = 27$  each), and following laboratory heating in the muffle furnace (3 replicates for each temperature/exposure time)

		Granular PyC		PyC pieces	
		Median mass loss (%)	Mass loss range (%)	Median mass loss (%)	Mass loss range (%)
Experimental 'wildfire'		6.6	0–70.4	15.1	0–100
Laboratory heating (time, duration)	370°C, 155 s	15.1	13.3–16.0	1.0	0.7–25.4
	470°C, 105 s	27.6	25.4–34.2	63.3	20.9–76.7
	570°C, 65 s	25.7	21.8–29.0	36.7	16.7–81.4

recorded on the forest floor during the fire. Peak temperatures were somewhat lower than in the field (Fig. 2). Peak temperatures measured inside the mesh bags were higher than those measured in the furnace, by  $\sim 50^\circ\text{C}$  in the trial at  $570^\circ\text{C}$  and  $\sim 100^\circ\text{C}$  at both  $470^\circ\text{C}$  and  $370^\circ\text{C}$  (data not shown).

The mass loss (%) for both granular PyC and PyC pieces under controlled heating is shown in Table 1. Variability among replicates was higher for PyC pieces than for the granular form. Exposure to  $370^\circ\text{C}$  for 155 s resulted in losses of granular PyC ranging from 13.3 to 16.0%. Under these conditions, only one PyC piece ignited (mass loss 25.4%), whereas the other two pieces did not ignite and therefore experienced negligible losses (1.0 and 0.7%). Exposure to  $470^\circ\text{C}$  for 105 s and to  $570^\circ\text{C}$  for 65 s produced very similar outcomes between them (Table 1): all PyC pieces were partially ignited and suffered substantial losses (16.7–81.4%). Overall, consumption of granular PyC was lower (21.8–34.2% of the initial mass) than for PyC pieces at these two experimental conditions. PyC consumption under laboratory trials was greater than under field conditions except for the PyC exposed to  $370^\circ\text{C}$  for 155 s (Table 1).

## Discussion

The FireSmart experimental fire reproduced fire conditions typical of boreal forest in this region and the combustion conditions can therefore be expected to resemble what may happen in an actual wildfire. The results indicate a rather limited combustion of residual PyC by a subsequent fire and, therefore, do not support the suggestion that wildfire in this boreal region is a major driver of PyC loss (e.g. Preston and Schmidt 2006; Czimeczik and Masiello 2007), at least as far as PyC present at the forest floor is concerned.

The additional exploratory laboratory heating experiments can serve only as a simplified attempt at reproducing some of the temperature-duration conditions that might be experienced in the field. They do, however, confirm an overall low, albeit somewhat higher, consumption of PyC at the conditions selected. The higher mass loss may be due to more effective combustion in the muffle furnace, which does not represent the often oxygen-limited conditions experienced at the forest floor during wildfire (Bryant *et al.* 2005).

To our knowledge, no other experimental or field data have been published that would allow comparison with our results. A wide range of studies have examined the effect of

experimental heating on bulk soil organic matter or on specific organic components of soils such as lipids, humic substances or peat (Almendros *et al.* 1988, 2003; Badía and Marti 2003; Tecimen and Sevgi 2011). However, none of them have examined the effect of heating on residual PyC. Only Hatten and Zabowski (2010) considered the effect of fire on 'indigenous' PyC (i.e. that already present in the soil) in some detail when investigating the effects of fire severity on soil organic matter in a pine forest. Unfortunately, they were not able to differentiate between the pre-existing and newly generated PyC. Hence, their only conclusion about residual PyC was that PyC within the mineral soil was not altered by burning due to a limited downward propagation of heat.

In terms of the wider applicability of our results, three issues warrant further consideration.

- The use of mesh bags may have resulted in an enhancement of combustion for granular PyC. The increased temperatures observed within the mesh bags compared to the furnace temperature during the laboratory heating experiments suggest that a local increase in heat generation was confined within them. It is therefore likely that the use of mesh bags increases PyC combustion and might lead to overestimation of PyC losses in both field and laboratory experiments.
- PyC samples were placed at  $\sim 2\text{-cm}$  depth within the forest floor, which resulted in PyC being located largely within the upper layer consumed by the fire. Following a fire, substantial amounts of PyC can indeed be found, often as part of ash deposits, on the forest floor (Santín *et al.* 2012) and could potentially be consumed in subsequent fires. However, this is likely to represent only a fraction of all PyC remaining on site after a fire. First, PyC present on standing or downed wood may also be quantitatively important (Donato *et al.* 2009). Second, PyC particles, like all smaller-sized surface material, can become buried by litter accumulation or migrate down the forest floor profile, eventually being incorporated into the mineral soil (Preston and Schmidt 2006). Even severe vegetation fires do not generally result in temperatures exceeding  $200^\circ\text{C}$  some millimetres below the mineral soil surface (González-Pérez *et al.* 2004; Doerr *et al.* 2006). Hence any residual PyC incorporated into the mineral soil matrix or

remaining within the organic surface layer, but below the depth of burn, will be protected from being consumed by fire. Third, not all PyC will necessarily remain on site. Particularly in areas with significant topography, surface PyC, together with the other components comprising ash, are often transported off-site within weeks of a fire (Cerdà and Doerr 2008; Rumpel *et al.* 2009), well before sufficient biomass may accumulate to fuel a subsequent fire.

- (iii) The charcoal tested here may be a relatively recalcitrant type of PyC due to both its source material (i.e. pine wood; e.g. Baldock and Smernik 2002) and its formation conditions (i.e. slash pile burn; e.g. Massman *et al.* 2003; Massman *et al.* 2008). During a forest wildfire, a whole range of PyC compounds are produced, not only from woody materials but also from non-woody materials such as leaves, lichens, mosses and litter. These different types of PyC, with different chemical and physical characteristics, will also respond differently to fire. It is therefore conceivable that more labile forms of PyC will suffer a higher degree of combustion. That said, the more labile forms of PyC produced in a fire undergo natural degradation first, leading to a relative enrichment of recalcitrant forms of PyC over time (Ohlson 2012). Thus 'older' PyC that is close enough to the surface to be susceptible to consumption by fire might indeed be more recalcitrant and, hence, somewhat more resistant to combustion.

Therefore, under our experimental conditions, issues (i) and (ii) may have led to overestimation, whereas (iii) to an underestimation of PyC losses compared with what could be expected under 'natural' conditions. Overall we suggest that the extent of PyC consumption found in our field experiment is likely to be an overestimation of the overall loss of previously formed PyC in a wildfire. The results are, at best, representative of the consumption of forest floor PyC that happens to be stored within the depth of burn zone at the time of a fire and is likely to be only a fraction of all PyC generated in a previous fire. In the North American boreal region, the fire recurrence interval ranges from ~150 to 200 years (Stocks *et al.* 2003; Balshi *et al.* 2009), allowing ample time for the redistribution of PyC between fires to locations where it could be protected from combustion.

## Conclusions

Given the relative importance of PyC production, storage and degradation in the global carbon cycle, the role of fire as a potential abiotic means of PyC degradation warrants consideration. The field results reported here, which, to our knowledge, provide the first quantitative data of losses of residual PyC by fire, do not support the widely held assumption that wildfire is a major driver of PyC loss. Instead, they indicate limited consumption of residual PyC present at the forest floor during a fire. To examine the wider applicability of these findings, additional data covering a broader range of ecosystems and PyC and fire types are needed. The experimental field approach developed in this study provides a simple approach to quantifying potential loss of residual PyC by a subsequent fire. This methodology could be readily adapted and improved upon for future investigations. The exploratory laboratory experiments conducted here add some insights into potential limitations of the

experimental approach used in the field. However, further development is required to improve the usefulness of laboratory heating experiments in reflecting conditions present during wildfire.

## Acknowledgements

Cristina Santín is grateful to the Spanish Ministry for a mobility postdoctoral fellowship (EX2010-0498). Fieldwork was supported by the College of Science of Swansea University by a Research Fund disbursement exercise. Special thanks to Ray Ault (FP-Innovations) and Larry Nixon (Environment and Natural Resources, GNWT) for enabling us to participate in the Fire-Smart project. Thanks also to the staff of FP Innovations and fire crews for their logistical support during fieldwork. The authors also thank Maria Cabo for laboratory assistance and the anonymous reviewers and editors for helpful comments.

## References

- Alexander ME, Stefner CN, Mason JA, Stocks BJ, Hartley GR, Maffey ME, Wotton BM, Taylor SW, Lavoie N, Dalrymple GN (2004) Characterizing the jack pine – black spruce fuel complex of the International Crown Fire Modelling Experiment (ICFME). Canadian Forest Service, Northern Forestry Centre, Information report NOR-X-393. (Ottawa, ON)
- Almendros G, Martin FJ, González-Vila FJ (1988) Effects of fire on humic and lipid fractions in a Dystric Xerochrept in Spain. *Geoderma* **42**, 115–127. doi:10.1016/0016-7061(88)90028-6
- Almendros A, Knicker H, González-Vila J (2003) Rearrangement of carbon and nitrogen forms in peat after progressive thermal oxidation as determined by solid-state <sup>13</sup>C- and <sup>15</sup>N-NMR spectroscopy. *Organic Geochemistry* **34**, 1559–1568. doi:10.1016/S0146-6380(03)00152-9
- Badía D, Martí C (2003) Effect of simulated fire on organic matter and selected microbiological properties of two contrasting soils. *Arid Land Research and Management* **17**, 55–69. doi:10.1080/15324980301594
- Baldock JA, Smernik RJ (2002) Chemical composition and bioavailability of thermally altered *Pinus resinosa* (Red pine) wood. *Organic Geochemistry* **33**, 1093–1109. doi:10.1016/S0146-6380(02)00062-1
- Balshi D, McGuire AD, Duffy P, Flannigan M, Walsh J, Melillo J (2009) Assessing the response of area burned to changing climate in western boreal North America using a Multivariate Adaptive Regression Splines (MARS) approach. *Global Change Biology* **15**, 578–600. doi:10.1111/J.1365-2486.2008.01679.X
- Bond-Lamberty B, Peckham SD, Ahl DE, Gower ST (2007) Fire as the dominant driver of central Canadian boreal forest carbon balance. *Nature* **450**, 89–92. doi:10.1038/NATURE06272
- Bryant R, Doerr SH, Helbig M (2005) Effect of oxygen deprivation on soil hydrophobicity during heating. *International Journal of Wildland Fire* **14**, 449–455. doi:10.1071/WF05035
- Cerdà A, Doerr SH (2008) The effect of ash and needle cover on surface runoff and erosion in the immediate post-fire period. *Catena* **74**, 256–263. doi:10.1016/J.CATENA.2008.03.010
- Cheng CH, Lehmann J (2009) Ageing of black carbon along a temperature gradient. *Chemosphere* **75**, 1021–1027. doi:10.1016/J.CHEMOSPHERE.2009.01.045
- Cheng CH, Lehmann J, Thies JE, Burton SD, Engelhard MH (2006) Oxidation of black carbon by biotic and abiotic processes. *Organic Geochemistry* **37**, 1477–1488. doi:10.1016/J.ORGGEOCHEM.2006.06.022
- Czimczik CI, Masiello CA (2007) Controls on black carbon storage in soils. *Global Biogeochemical Cycles* **21**, GB3005. doi:10.1029/2006GB002798
- Czimczik CI, Schmidt MWI, Schulze ED (2005) Effects of increasing fire frequency on black carbon and organic matter in Podzols of Siberian Scots pine forest. *European Journal of Soil Science* **56**, 417–428. doi:10.1111/J.1365-2389.2004.00665.X

- de Groot WJ, Pritchard JM, Lynham TJ (2009) Forest floor fuel consumption and carbon emissions in Canadian boreal forest fires. *Canadian Journal of Forest Research* **39**, 367–382. doi:10.1139/X08-192
- Doerr SH, Shakesby RA, Blake WH, Humphreys GS, Chafer C, Wallbrink PJ (2006) Effects of differing wildfire severity on soil wettability in Australian eucalypt catchments. *Journal of Hydrology* **319**, 295–311. doi:10.1016/J.JHYDROL.2005.06.038
- Donato DC, Campbell JL, Fontaine JB, Law BE (2009) Quantifying char in postfire woody detritus inventories. *Fire Ecology* **5**, 104–115. doi:10.4996/FIREECOLOGY.0502104
- Foeroid B, Lehmann J, Major J (2011) Modeling black carbon degradation and movement in soil. *Plant and Soil* **345**, 223–236. doi:10.1007/S11104-011-0773-3
- Goldberg ED (1985) 'Black carbon in the environment.' (Wiley: New York)
- González-Pérez JA, González-Vila FJ, Almendros G, Knicker H (2004) The effect of fire on soil organic matter – a review. *Environment International* **30**, 855–870. doi:10.1016/J.ENVINT.2004.02.003
- Harden JW, Trumbore SE, Stocks BJ, Hirsch A, Gower ST, O'Neill KP, Kasischke ES (2000) The role of fire in the boreal carbon budget. *Global Change Biology* **6**, 174–184. doi:10.1046/J.1365-2486.2000.06019.X
- Hatten JA, Zabowski D (2010) Fire severity effects on soil organic matter from a ponderosa pine forest: a laboratory study. *International Journal of Wildland Fire* **19**, 613–623. doi:10.1071/WF08048
- Hilscher A, Knicker H (2011a) Degradation of grass-derived pyrogenic organic material, transport of the residues within a soil column and distribution in soil organic matter fractions during a 28 month microcosm experiment. *Organic Geochemistry* **42**, 42–54. doi:10.1016/J.ORGGEOCHEM.2010.10.005
- Hilscher A, Knicker H (2011b) Carbon and nitrogen degradation on molecular scale of grass-derived pyrogenic organic material during 28 months of incubation in soil. *Soil Biology & Biochemistry* **43**, 261–270. doi:10.1016/J.SOILBIO.2010.10.007
- Kane ES, Hockada WC, Turetsky MR, Masiello CA, Valentine DW, Finney BP, Baldock JA (2010) Topographic controls on black carbon accumulation in Alaskan black spruce forest soils: implications for organic matter dynamics. *Biogeochemistry* **100**, 39–56. doi:10.1007/S10533-009-9403-Z
- Kuzyakov Y, Subbotina I, Chen H, Bogomolova I, Xu X (2009) Black carbon decomposition and incorporation into soil microbial biomass estimated by <sup>14</sup>C labelling. *Soil Biology & Biochemistry* **41**, 210–219. doi:10.1016/J.SOILBIO.2008.10.016
- Lehmann J, Skjemstad J, Sohi S, Carter J, Barson M, Falloon P, Coleman K, Woodbury P, Krull E (2008) Australian climate–carbon cycle feedback reduced by soil black carbon. *Nature* **358**, 832–835.
- Liang B, Lehmann J, Solomon D, Sohi S, Thies JE, Skjemstad JO, Luizao FJ, Engelhard MH, Neves EG, Wirick S (2008) Stability of biomass-derived black carbon in soils. *Geochimica et Cosmochimica Acta* **72**, 6069–6078. doi:10.1016/J.GCA.2008.09.028
- Lizhong Y, Yupeng Z, Yafei W, Zaifu G (2008) Predicting charring rate of woods exposed to time-increasing and constant heat fluxes. *Journal of Analytical and Applied Pyrolysis* **81**, 1–6. doi:10.1016/J.JAAP.2007.06.006
- Malamud BD, Morein G, Turcotte DL (1998) Forest fires: an example of self-organized critical behavior. *Science* **281**, 1840–1842. doi:10.1126/SCIENCE.281.5384.1840
- Massman WJ, Frank JM, Shepperd WD, Platten MJ (2003) *In situ* soil temperature and heat flux measurements during controlled surface burns at a southern Colorado forest site. In 'Fire, Fuel Treatments, and Ecological Restoration: Conference Proceedings', 16–18 April 2002, Fort Collins, CO. (Eds PN Omi, LA Joyce) USDA Forest Service, Rocky Mountain Research Station, Proceedings RMRS-P-29, pp. 69–87. (Fort Collins, CO)
- Massman WJ, Frank JM, Reisch NB (2008) Long-term impacts of prescribed burns on soil thermal conductivity and soil heating at a Colorado Rocky Mountain site: a data/model fusion study. *International Journal of Wildland Fire* **17**, 131–146. doi:10.1071/WF06118
- Ohlson M (2012) Soil charcoal stability over the Holocene – comment to the paper published by de Lafontaine and Asselin, Quaternary Research, v. 76, 2011, pp. 196–200. *Quaternary Research* **78**, 154. doi:10.1016/J.YQRES.2012.03.007
- Ohlson M, Tryterud E (2000) Interpretation of the charcoal record in forest soils: forest fires and their production and deposition of macroscopic charcoal. *The Holocene* **10**, 519–525. doi:10.1191/095968300667442551
- Preston CM, Schmidt MW (2006) Black (pyrogenic) carbon: a synthesis of current knowledge and uncertainties with special consideration of boreal regions. *Biogeosciences* **3**, 397–420. doi:10.5194/BG-3-397-2006
- Rumpel C, Ba A, Darboux F, Chaplot V, Plançon O (2009) Erosion budget and process selectivity of black carbon at meter scale. *Geoderma* **154**, 131–137. doi:10.1016/J.GEODERMA.2009.10.006
- Santín C, Doerr SH, Shakesby RA, Bryant R, Smith HG, Sheridan GJ, Lane PNJ, Bell TL (2012) Carbon forms in and sequestration potential from ash deposits from forest fires: a case of study from the 2009 Black Saturday fires, Australia. *European Journal of Forest Research* **131**, 1245–1253. doi:10.1007/S10342-012-0595-8
- Santos F, Torn MS, Bird JA (2012) Biological degradation of pyrogenic organic matter in temperate forest soils. *Soil Biology & Biochemistry* **51**, 115–124. doi:10.1016/J.SOILBIO.2012.04.005
- Schmidt MWI, Torn MS, Abiven S, Dittmar T, Guggenberger G, Janssens IA, Kleber M, Kögel-Knaber I, Lehman J, Manning DAC, Nannipieri P, Rasse DP, Weiner S, Trumbore SE (2011) Persistence of soil organic matter as an ecosystem property. *Nature* **478**, 49–56. doi:10.1038/NATURE10386
- Seedre M, Shrestha BM, Chen HYH, Colombo S, Jogiste K (2011) Carbon dynamics of North American boreal forest after stand replacing wildfire and clearcut logging. *Journal of Forest Research* **16**, 168–183. doi:10.1007/S10310-011-0264-7
- Stocks BJ, Mason JA, Todd JB, Bosch EM, Wotton BM, Amiro BD, Flannigan MD, Hirsch KG, Logan KA, Martell DL, Skinner WR (2003) Large forest fires in Canada, 1959–1997. *Journal of Geophysical Research* **108**, 8149. doi:10.1029/2001JD000484
- Tecimen HB, Sevgi O (2011) Heating induced changes in mineral nitrogen and organic carbon in relation with temperature and time. *Journal of Environmental Biology* **32**, 295–300.
- Zimmerman AR, Gao B, Ahn MY (2011) Positive and negative carbon mineralization priming effects among a variety of biochar-amended soils. *Soil Biology & Biochemistry* **43**, 1169–1179. doi:10.1016/J.SOILBIO.2011.02.005