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Presence of Black Carbon in Soil due to Forest Fire in the New Jersey Pine Barrens

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Abstract: Fire is an important ecological factor and what constitutes appropriate fire management is much debated in the US and elsewhere. The role of fire as a source of greenhouse gases has been intensively investigated, but less is known about the production rate of the solid black carbon residue from fires. Black carbon accumulates in soil as it has longer turnover times than plant residues. To understand the significance of black carbon production during wildfire, we quantified black carbon using hydropyrolysis in O and A horizons before and after a prescribed burn at four sites in the New Jersey Pine Barrens forest in the North-Eastern US. Black carbon was found in both O- and A-horizons at all investigated sites, stocks in the range of 61.31-168.15 g m^{-2} in the O-horizon and 169.59-425.25 g m^{-2} in the A-horizon. Total black carbon stocks did not increase following the fire suggesting that either black carbon production in fires may be small compared to the variability, or that equivalent amounts of black carbon formed in previous fires may have been consumed in the fire. The study raises questions about how black carbon production and consumption in fires can be quantified separately.

Key words: Black carbon, soil properties, prescribed fire, New Jersey Pine Barrens.

1. Introduction

Fire has historically been the most significant natural and human-induced disturbance to forest and grassland ecosystems in North America and is considered to be among the major drivers of ecosystem processes in these ecosystems and the global carbon cycle [1-2]. Fire management is an important topic in the debate about conservation and natural resource management in the US [3]. Traditionally, fire has been used by indigenous populations to manage ecosystems for millennia prior to European arrival [4]. Europeans initially mostly favored fire suppression, but prescribed burning as a management tool has now gained acceptance, although the details of what constitutes appropriate fire management are still hotly debated [3, 5]. Currently, most assessments of fires and forest greenhouse gas budgets focus on carbon dioxide emissions [6-9] and fire is counted as a process that only consumes biomass in IPCC (Intergovernmental Panel on Climate Change) guidelines for tier one reporting [10]. However, productivity commonly increases after fire and frequent low-severity fires may decrease the risk of catastrophic fires that reduce carbon storage to a greater extent [11]. In addition a small amount of black carbon is produced by fires [12-15] and studies of black carbon stability in soil suggest that it may also sequester carbon for centuries or even millennia [16-20].

Although the production of black carbon is small as a percentage of total vegetation carbon consumed in the fire (~1%-10%; [15]), it is still important in the global carbon cycle on longer timescales. Its formation is often credited as a CO_2 sink by transferring fast-cycling carbon from the

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atmosphere-biosphere system into much slower cycling carbon forms. To obtain a full accounting of the effect of fire on the carbon cycle, and therefore also on the climate system, both carbon emissions as well as sequestration of black carbon in the soil must be taken into account. Few data exist on black carbon production from temperate forest fires [20, 21], with somewhat better data available from slash and burn events in tropical and sub-tropical forests as well as fires in tropical savannas [15, 22]. Furthermore, quantification of black carbon is technically difficult.

The objective of this study was to quantify changes in soil black carbon as a result of fire in a temperate forest using hydrogen pyrolysis to quantify changes in soil black carbon content as a result of fire.

2. Methods

2.1 Site Description

The field site is located at Pine Barrens, Butler Place, southern New Jersey, USA (39.8726° N, 74.5013° W, 40 m elevation). The climate is cool temperate, with mean monthly temperatures of 0.3 and 23.8 ºC in January and June, respectively (1930-2004; State Climatologist of New Jersey). Mean annual precipitation is 1,123 ± 182 mm. Soils are derived from the Cohansey and Kirkwood Formations, and are sandy, coarse-grained, with extremely low nutrient status [23]. The vegetation is dominated by Pitch pine (*Pinus rigida* Mill.) overstory, blueberry (*Vaccinium* spp.) and shrub oak (*Quercus ilicifolia* Wang, *Q. marlandica* Muench.) understory. This landscape was also previously characterized by a high frequency and intensity of wildfires relative to other forest ecosystems in the north-eastern US [24, 25].

Many pine forest systems such as this are, in their natural state, maintained by relatively frequent, low-impact fires that consume the litter layer, but do not kill the trees. The Pine Barrens site is a biosphere reserve [26], and part of the management at this site is prescribed burning with the main objective of burning being to reduce fuel load and thereby the threat of more severe crown fires (e.g. [27, 28]). Some blocks have been burned every 5-8 years since the late 1950’s. As far as known, the entire area studied here has the same fire history.

2.2 Sampling

Four sampling locations were established, all located next to atmospheric measurement towers (Table 1). The sampling points were chosen to span the variation in soil moisture as well as the geographical extent of the forest as representative sites. The soil at site 4 was notably drier than at the other sites. At each sampling location, three sampling points with a diameter of 0.5 m were established spaced evenly along the perimeter of a 10 m diameter area. At each sampling point 3 soil cores were taken and composited. Within each sampling point, samples were taken to 10-50 mm below the organic layer with a 50 mm diameter corer. The depth varied because the thickness of horizons varied. The organic layer was separated from the mineral soil by hand using visual clues (i.e. color and presence of plant litter) to determine the extent of each horizon. Thicknesses of both the organic and mineral horizons were measured for bulk density determination, but only during the pre-fire sampling. It was not possible to measure thickness accurately during the post-fire sampling because it rained just after the fire and the samples were wet. To calculate carbon stocks it was assumed that A-horizon was 5 cm thick in all cases, and the pre-fire values for bulk density were applied for both sampling periods. As prescribed burns at this site are typically scheduled at very short notice during the fire season, pre-fire sampling was done just before the start of the fire season, on February 18th. The site was burned on 20th March, and post fire sampling was carried out early the next day.

2.3 Fire Characteristics

The fire itself is described in detail by Heilman *et al.* [29]. Maximum one-minute temperatures during the fire were 47.3 °C at 20 m and 60.5 °C at 3 m when the

Table 1 Soil parameters at the four sites sampled. Values are averages with standard error in brackets (n = 3).

	Site 1		Site 2		Site 3		Site 4	
	O horizon	A horizon	O horizon	A horizon	O horizon	A horizon	O horizon	A horizon
Carbon (mg g^{-1})								
pre-fire	255.6 (37.5)	37.0 (10.5)	312.9 (67.3)	43.9 (12.6)	244.5 (10.4)	52.0 (19.2)	105.5 (18.8)	14.9 (3.0)
post-fire	194.8 (29.7)	52.2 (33.3)	296.7 (53.4)	51.2 (4.9)	271.9 (60.1)	33.7 (7.9)	211.1 (56.6)	49.2 (23.2)
Nitrogen (mg g^{-1})								
pre-fire	7.36 (1.29)	0.98 (0.31)	8.42 (1.59)	0.95 (0.25)	6.89 (0.63)	1.19 (0.45)	3.33 (0.55)	0.32 (0.08)
post-fire	5.64 (0.97)	1.24 (0.81)	7.46 (1.43)	1.09 (0.11)	7.86 (2.07)	0.81 (0.20)	5.53 (1.27)	1.02 (0.44)
Carbon:Nitrogen								
pre-fire	35.1 (1.5)	38.9 (1.8)	36.7 (1.9)	45.0 (2.2)	36.8 (1.6)	43.3 (1.6)	31.6 (0.8)	48.1 (4.0)
post-fire	34.8 (0.0)	43.3 (2.5)	40.0 (0.5)	47.2 (4.0)	35.3 (1.4)	41.7 (0.6)	37.6 (1.3)	47.1 (2.4)
Bulk density (g cm^{-3})								
	0.22 (0.04)	0.90 (0.34)	0.27 (0.04)	0.90 (0.10)	0.29 (0.03)	1.05 (0.12)	0.48 (0.05)	1.39 (0.09)
pH (water)								
pre -fire	3.80 (0.12)	4.13 (0.13)	3.82 (0.11)	4.05 (0.08)	3.67 (0.10)	4.35 (0.13)	3.67 (0.10)	4.35 (0.13)
post-fire	3.96 (0.07)	3.70 (0.18)	3.97 (0.16)	4.06 (0.04)	3.85 (0.03)	4.16 (0.03)	3.89 (0.09)	4.14 (0.21)
BC (% of soil)								
pre-fire	0.48 (0.09)	0.47 (0.07)	1.01 (0.14)	0.91 (0.33)	1.49 (0.34)	0.95 (0.19)	0.53 (0.28)	0.22 (0.07)
post-fire	0.75 (0.17)	0.63 (0.39)	1.80 (0.22)	0.97 (0.19)	0.74 (0.16)	0.33 (0.03)	0.78 (0.35)	0.29 (0.08)
BC (% of TOC)								
pre-fire	2.05 (0.62)	14.53 (4.66)	3.52 (0.75)	19.90 (3.25)	6.01 (1.20)	21.62 (4.81)	4.60 (1.88)	15.29 (4.00)
post-fire	3.81 (0.40)	12.51 (1.03)	6.30 (0.89)	18.81 (0.89)	3.10 (1.19)	10.58 (2.04)	3.39 (0.64)	6.85 (1.15)
BC (g m^{-2})								
pre-fire	44.4 (18.2)	217.4 (103.8)	106.2 (20.0)	422.8 (189.8)	126.3 (20.9)	480.4 (71.8)	92.6 (59.7)	146.1 (39.2)
post-fire	65.8 (18.2)	412.7 (103.8)	168.2 (20.0)	423.3 (189.8)	61.3 (20.9)	169.6 (71.8)	76.5 (59.7)	169.7 (39.2)

fire front passed at about 1520 EDT. There was no reliable measurement of ground temperature during the fire, but and IR camera measured values above the saturation temperature of 650 °C. Typical ground temperature for low level ground fires like this is 700-800 °C (Hom pers comm). Wind direction was south-easterly before the fire, turning southwesterly immediately before and during the passage of the fire front. It was estimated that 47% of total fuel loading at the site burned during the fire [29]. The effect of the fire on biomass and overall carbon budget is described elsewhere [30].

2.4 Sample Treatment and Analysis

Samples were air dried and weighed and stored until analysis. Soil pH (in water at 1:2.5 w/v) was determined on untreated samples. Sub-samples were then ball-milled to < 100 mesh. Soil carbon and nitrogen content was determined with a LECO combustion analyzer (St. Joseph, MI). Black carbon was quantified by hydrogen pyrolysis (hypy). Hypy has been described in detail in a number of publications [31-35]. Briefly, the solid samples were loaded with a Mo catalyst using an aqueous/methanol solution of ammonium dioxydithiomolybdate [$(NH_4)_2MoO_2S_2$]. Catalyst weight was ~5% sample weight. Approximately 50-100 mg of dried catalyst loaded samples were placed in a reactor of the hypy unit (Strata Technology Ltd, Sunbury-on Thames, Middlesex UK) and pressurized under 150 bar hydrogen under a sweep gas flow of 5 L min^{-1}, then heated slowly using a pre-programmed temperature profile. We used the recommended temperature program previously optimized for black carbon where samples initially were heated at 300 °C min^{-1} until 250 °C, then stepped at 8 °C min^{-1} until a final hold temperature of 550 °C for 2 minutes [34, 35].

Carbon concentrations of samples after the procedure were determined using a Costech Elemental Analyzer (Costech Analytical Technologies Inc Valencia, California, USA) fitted with a zero-blank auto-sampler. Because catalyst and mineral components undergo weight loss during hypy, the abundance of black carbon in the sample after hydrogen pyrolysis was determined relative to total organic carbon.

2.5 Statistical Analysis

Statistical analysis was done with SPSS (statistical Package for Social Scientists) statistics v20. Sites were compared using an Anova, and values of measured variables before and after fire at individual sites were compared with a t-test.

3. Results

There was little difference between the sites before fire (Table 1), with the exception of the site 4 soils which had a significantly higher bulk density than all the other sites in the O-horizon and higher bulk density than one of the other sites in the A-horizon. Visible black carbon was only identified at site 4 in the A-horizon. However, based hypy analysis, black carbon was found both in the A- and the O-horizons before the fire at all the sites (Table 1). There was no significant difference in black carbon content between sites in either horizon. The black carbon proportion of soil mass was also not very different between A and O horizon or between sites, but the stock estimates were more variable (61.31-168.15 g m^{-2} in the O-horizon and 169.59-425.25 g m^{-2} in the A-horizon, Table 1).

The soil surface was visibly black after fire in the entire forest, but the litter layer was only partially burnt. Dead trees were lying and still burned the next day, and may burn almost completely, whilst live trees and shrubs were not significantly affected by the fire. Carbon to nitrogen ratio was significantly higher after than before fire in the O-horizon at site 4. There was no significant difference in pH measured before and after fire, although there was a tendency for pH to be higher after the fire at one of the sites (site 4). Changes in the amount of black carbon before and after fire were small and inconsistent between sites (Fig. 1). The only significant difference between before and after fire was a decrease in the A-horizon at site 3.

4. Discussion

In our study, soil black carbon contents measured using hypy did not increase as a result of the fire. This is surprising, and suggests that black carbon production

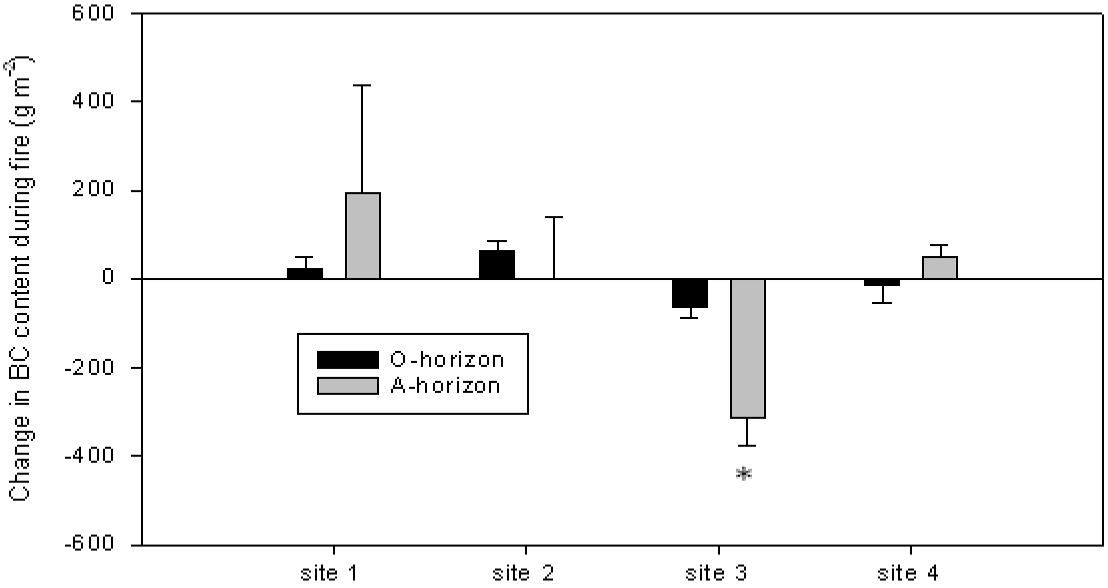

Fig. 1 Changes in black carbon stocks between before and after fire in both O and A horizons at four studied sites in New Jersey Pine Barren forests. Error bars are standard error (n = 3). Star indicates significant change (i.e. change significantly different from zero).

may be small and/or re-burning of black carbon already present in the soil may be a significant process. It is also possible that as this was a low intensity fire, charring was so light that the hypy methodology did not capture weakly aromatic char [35]. However, low black carbon production is a possibility as previous studies have also found that recent fire history and fire frequency had little effect on the amount of black carbon found in the soil [36, 37] or transported in waterways [38]. Re-burning of black carbon may have played a role [39] but may have been spatially highly variable depending on fuel and soil moisture [40]. However, a recent study quantifying charcoal burning found low mass loss of pre-existing charcoal after fire in a boreal forest and also under laboratory conditions [41].

Our study confirms that black carbon is present in both horizons, in similar concentrations (per unit soil mass). The fact that small pieces of black carbon not observable by the naked eye, were found in the O-horizon also before the fire indicates that this horizon has not been completely consumed by previous fires, and black carbon has not moved to a great extent.

The effects of fire on other soil properties were also minor. This is consistent with the results of Neill et al. [42] who found that the effects of burning regime on soil properties were minor in an oak-pine forest in Cape Cod, Northeastern USA. The only significant change after the fire in this study was a significant increase in the carbon to nitrogen ratio in the O-horizon at site 4. This is somewhat in contrast to Gundale et al. [43] who found burned sites had lower carbon to nitrogen ration in a Montana ponderosa pine forest. The reason why carbon to nitrogen ratio increased in this study at the driest site may be that the nitrogen-rich part of the litter was preferentially consumed by the fire.

It was qualitatively observed that dead trees burned more or less completely. It is possible that this may also produce large quantities of black carbon with a very patchy distribution, and this may even be the largest source of black carbon. To quantify black carbon production, the number of such production hotspots would need to be quantified over a larger area, as well as the average production of black carbon for each hotspot. Soil sampling according to fuel abundance and extrapolation using remotely sensed data may be a more promising approach than randomized soil sampling.

The results of this study also raise questions about how black carbon production in natural fires can be quantified, and even whether it can be reliably quantified. Black carbon content in soils is naturally spatially and potentially also temporally variable. It is possible that this variability obscure any small changes that may have occurred as a result of an individual fire.

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