Research Note

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Fire ignition patterns affect production of charcoal in southern forests

Eric Oliveira Carvalho[A], *Leda N. Kobziar*[A,C] *and Francis E. Putz*[B]

[A]School of Forest Resources and Conservation, 371 Newins-Ziegler Hall, University of Florida, Gainesville, FL 32611, USA.
[B]Department of Biology, University of Florida, Gainesville, FL 32611, USA.
[C]Corresponding author. Email: lkobziar@ufl.edu

Abstract. Although charcoal represents a relatively minor portion of available biomass burned in wildfires and prescribed burns, its recalcitrant properties confer residence times ranging from centuries to millennia, with significance for carbon sequestration in frequently burned forests. Here, we determined whether charcoal formation differed between the two most common prescribed fire spread patterns in southern forests: head (with the wind) and backing (against the wind). Pine wood samples were distributed randomly within a mesic flatwoods burn unit in north-central Florida, and subjected either to a head fire ($n = 34$) or a backing fire ($n = 34$). Backing fires formed more than twice as much charcoal as head fires (1.53 *v.* 0.38% of available biomass), presumably because of differences in residence times, oxygen availability and fire intensity between the two fire spread patterns. These results suggest that the contribution of charcoal to ecosystem carbon sequestration is greater when flatwoods forests are burned against the prevailing wind direction, and that further investigation of these trends is warranted.

Additional keywords: black carbon, carbon sequestration, prescribed fire, pyrogenic carbon.

Introduction

Soil carbon (C) has been estimated to comprise ~70% of the world's total terrestrial C pools (Post *et al*. 1982), and biomass burning is known to have considerable influence on soil carbon dynamics and storage (Preston and Schmidt 2006; Alexis *et al.* 2007; Lavoie *et al.* 2010). Fire converts C stored in biomass, necromass and the forest floor into gaseous forms such as CO_2, CO and CH_4, with a relatively minor portion converted into pyrogenic carbon, or charcoal (Preston and Schmidt 2006). Whereas fire has been linked with atmospheric C losses of between 40 and 84% of initial aboveground available biomass (Kauffman *et al.* 1994; Alexis *et al.* 2007; Lavoie *et al.* 2010), estimates for charcoal production range from 0.6 to 8% (Kuhlbusch and Crutzen 1995; Alexis *et al*. 2007). Although the contribution of charcoal may be small, its highly recalcitrant constituents suggest it contributes substantially to total soil C in frequently burned forests.

Charcoal can be defined as the visually identified portion of pyrogenic carbon produced during fires, and is formed by incomplete oxidation of plant material that occurs as a result of combustion in limited-oxygen environments (Preston and Schmidt 2006). Interest in charcoal is increasing for various reasons, both ecological and in regards to its role in long-term C storage. Charcoal is known to increase soil cation exchange capacity and soil water-holding capacity, and to increase soil porosity and aeration by decreasing bulk density (reviewed in Glaser *et al*. 2002). It also includes exceedingly stable forms of C that resist decomposition in soil (e.g. black carbon), with estimated residence times of 3000–12 000 years (DeLuca and Aplet 2008).

Little is known about the amount of charcoal formed during prescribed fires. DeLuca and Aplet (2008) estimated that in prescribed burns in ponderosa pine (*Pinus ponderosa*) forests, charcoal formation ranged from 0.07 to 0.72 $Mg\,C\,ha^{-1}$. However, these estimates were indirect, and based on two major assumptions: that charcoal is 80% C and that charcoal formation accounts for 1–10% of fuel consumed (charcoal was not measured directly). Considering that prescribed burning is a widespread practice across the south-eastern US, it is important to quantify charcoal formation in this region, and to determine whether different burn patterns affect the percentage of biomass converted into charcoal. Prescribed fires can be manipulated to burn against (backing) or with (head) the predominant wind direction, allowing researchers to question both the quantity of charcoal formed, and the fire behaviour that maximises charcoal formation and hence long-term soil C sequestration.

Prescribed fire spread patterns are controlled via ignition techniques. Fires spread in all directions, but the relationship between wind, slope and fire spread is controlled by igniting fires upwind (backing fire), downwind (head fire), or in the middle (spot, flank or grid fire) of unburned areas with available fuels (Wade and Lunsford 1989). Each fire spread pattern has different behaviour characteristics, even if fuel and weather conditions are held constant (Carroll *et al*. 1977; Fernandes *et al*. 2009). For example, because head fires move with the wind, they spread and burn fuel at faster rates, with higher fire intensity

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(kW m^{-1}), larger flaming zone depths of both flaming and smouldering combustion, and higher amounts of smoke produced (largely due to the by-products of smouldering combustion; Carroll *et al*. 1977). In contrast, backing fires have lower intensities, shorter flame lengths, slower rates of spread (Wade and Lunsford 1989), and have been shown to produce half the amount of smoke (Carroll *et al*. 1977). These fire behaviour factors are known to differentially affect injuries to overstorey trees, plant mortality and vegetation recovery (Outcalt and Foltz 2004; Snyman 2005). In either case, the amount of charcoal remaining on site following a fire increases as the proportion of complete combustion decreases. How ignition techniques affect the efficiency of combustion and the resulting charcoal formation is largely unknown.

We measured the differences in charcoal formation between head and backing fires during a prescribed burn in mesic flatwoods, which represent the most abundant forest type in the Southern Coastal Plain region. These forests are maintained on a tri-annual burn cycle. We tested the hypothesis that charcoal formation in pine wood blocks (100-h fuel class) was higher in backing fires than in head fires. A better understanding of the factors influencing charcoal formation can help forest managers sequester more C from prescribed burns in southeastern flatwoods forests.

Methods

Field site

This study was conducted in 2009 just north of Gainesville, Florida, in the University of Florida's Austin Cary Memorial Forest (29°44′N, 82°12′W). The compartment has been burned on a 3-year prescribed fire interval since 2003. The prescribed fires for the present study took place on 9 and 10 February 2009,

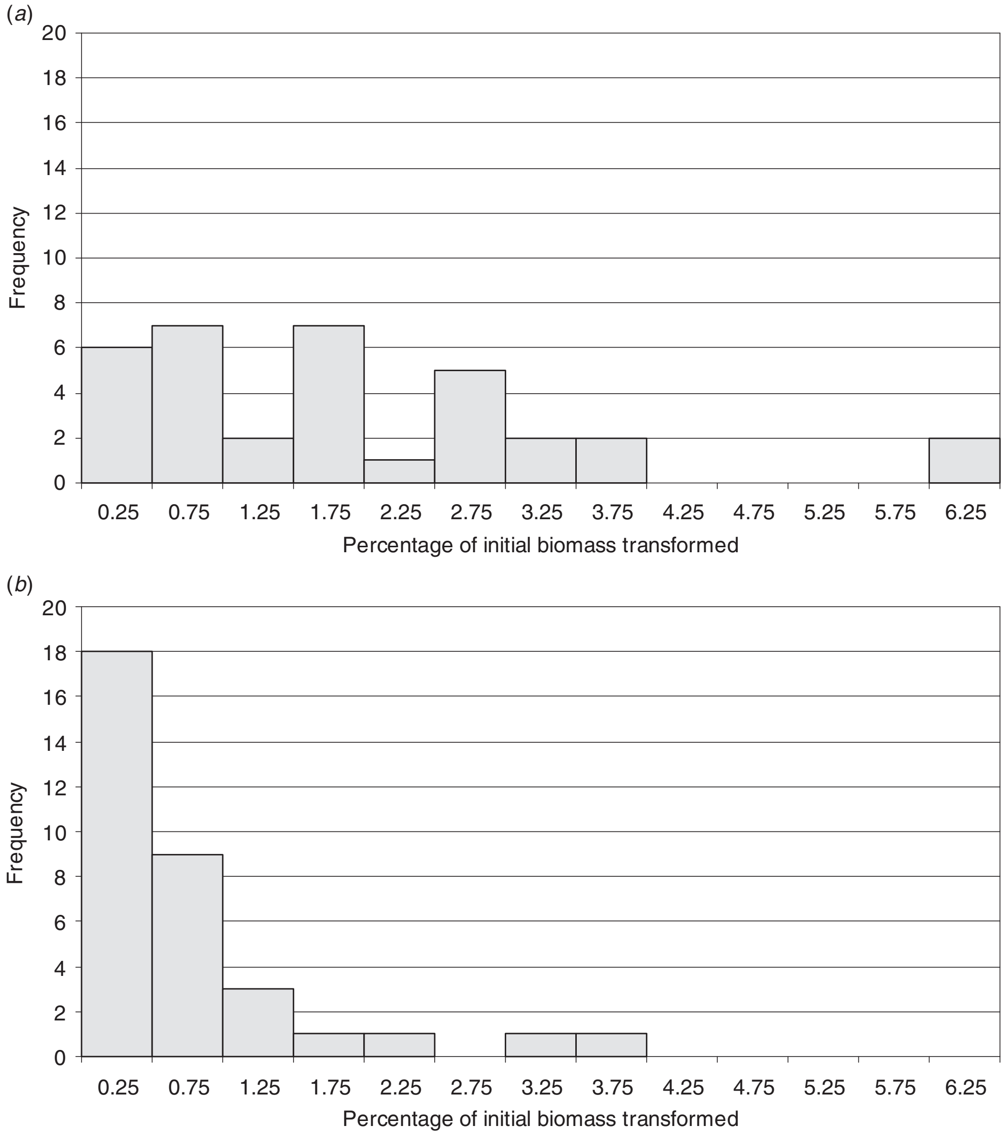

Fig. 1. Frequency of wood blocks' biomass transformed into charcoal during backing fire (*a*) and head fire (*b*) during a prescribed burn in north-central Florida pine flatwoods forests, expressed as a percentage of each block's initial biomass.

with ESE–SE winds that averaged 16 km h^{-1}, maximum temperatures of 21–24°C, and relative humidity of 30–45%. The stand has a mixed slash pine (*Pinus eliottii*) and longleaf pine (*P. palustris*) overstorey with gallberry (*Ilex glabra*), saw palmetto (*Serenoa repens*) and wiregrass (*Aristida stricta*) understorey. Pine needles, grasses and understorey vegetation were the primary carriers of fires during the prescribed burns, with a 10-h fuel moisture content of 10–15%. The ignition patterns consisted of strip fires lit with a drip torch in lines perpendicular to the wind direction and extending from one end of the unit to the other at regular intervals (5–10 m apart).

To determine whether charcoal production differed between ignition techniques, pine wood blocks ($n = 68$) were placed at 2-m intervals along randomly located transects running parallel to the ignition lines. Pine blocks on the downwind side of a given ignited strip were exposed to head fires while those blocks located upwind from the strips were exposed to a backing fire. Head fire strips and backing fire strips were ignited independently. There were multiple lines of fire ignited for each of the ignition types, and some fire lines burned more than one set of blocks. Each pine block (pine wood) was $3.8 \times 3.8 \times 10$ cm (i.e. 100-h fuel class). Each block was weighed before the burn and the weights averaged 70.13 g (s.d. $\pm$9.03 g). After the fires, each block was recovered, and identified by its assigned number. The charcoal component of each block was scraped off with a knife and weighed under controlled laboratory conditions. Charred wood was not oven-dried before weighing, and may have accumulated ambient moisture from the laboratory environment. To control for this possibility, we evaluated how much moisture oven-dried charcoal absorbed in the laboratory, and added this error term to the evaluation of the percentage of wood converted to charcoal during the burns (5.3% moisture absorbed from ambient relative humidity of 35%).

Data analysis

Data were not normally distributed (q-q plot, Shapiro–Wilk test, and see Fig. 1), and variances were not equal (F test), so a Wilcoxon Rank Sum test was used to compare the treatments. Results were expressed on the basis of percentage of initial biomass converted into charcoal. All analyses were performed in R.

Results

Our hypothesis that backing fires formed more charcoal was strongly supported by the data. Whereas percentage charcoal formed per initial biomass of wood block had a median of 0.38% (range 0 to 3.56%) for head fires, the median for backing fire was 1.53% (range 0.03 to 6.21%).

A higher percentage of charcoal was formed during backing fire than during head fire ($W = 887$, $P < 0.001$). Two pine blocks did not form any charcoal during head fires, because they did not ignite rather than because they were consumed by the fire. Less than 1% of biomass was converted to charcoal in nearly three-quarters of the blocks subjected to head fire, whereas the same was true for only 33% of the blocks burned using backing fire (Fig. 1).

Discussion

On average, a small proportion of pine wood block initial biomass was transformed into charcoal (0–6.21%). This falls within the range of estimates from fire experiments in a Florida southeastern scrub oak ecosystem, where charcoal formation represented 4–6% of initial biomass (Alexis *et al.* 2007), and also in a western US pine forest (1 to 10%; DeLuca and Aplet 2008). Neither of these studies quantified fire behaviour factors or differentiated between fire spread patterns. In the present study, backing fires formed significantly more charcoal than head fires, indicating a relationship between the fire behaviour associated with ignition patterns and the percentage of biomass converted into charcoal. The differences in charcoal formation were expected given that head and backing fires have different behaviour characteristics, which affect plant mortality, litter consumption, and, as demonstrated in this study, charcoal production. Backing fires are known to move at lower speeds, burn at lower temperatures, and produce shorter flame lengths than head fires. Given the slower rates of spread, fire residence times may have been longer in backing fires, which would result in localised oxygen depletion, favouring incomplete combustion and charcoal production. Differences in how fire spreads during the head *v.* backing fire may have also contributed to our results. Head fires spread from shrub to shrub, with minimal combustion or fire spread occurring in the ground fuels, where the wood blocks were located.

Our work indicates that by manipulating prescribed fire ignition techniques, it is possible to produce different amounts of charcoal. As charcoal likely plays a role in long-term C sequestration, manipulating burn patterns to maximise charcoal formation could become an important feature of forest management plans in the future. The consequences for overall C storage may be important, especially where prescribed burning is frequent and intervals are maintained over the long term. Additional studies are therefore warranted to corroborate these results, to investigate fire behaviour effects on both recalcitrant and labile C pools, and to expand the analysis to other ecosystems frequently burned across the southern US region and beyond.

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