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Charcoal re-combustion efficiency in tropical savannas

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ABSTRACT

Mass balance considerations suggest a significant gap in our understanding of the processes by which pyrogenic carbon (PC) is re-mineralized in the environment. Re-combustion by subsequent fires has been evoked as a plausible mechanism explaining significant losses of PC in fire-prone ecosystems, a claim not yet backed up with experimental data. In this study, four burning experiments were conducted in two northern Australian open savanna woodlands subject to regular prescribed fires to specifically assess charcoal re-combustion. The experimental burns were designed to provide a set of biotic and abiotic conditions capable of maximizing the re-ignition potential of surface charcoal fragments. We also tested whether the size of charcoal fragments had a significant effect on their combustion potential.

Although temperature profiles for each burn indicated that the conditions for potential combustion of the charcoal were met, out of the 264 charcoal pieces being monitored only five were totally combusted. Charcoal mass losses were independent of particle size, and averaged less than 8%. The results suggest that turnover times for charcoal in tropical savannas as a result of re-combustion alone are on the order of one century. The comparatively long turnover time ascertained under experimental conditions designed to maximize charcoal re-burning potential shows that re-combustion is not an efficient sink for pyrogenic carbon in tropical savannas. This finding strongly suggests that other processes must play a more substantial role in the re-mineralization of charcoal in order to balance the PC budget in these ecosystems.

1. Introduction

Global Pyrogenic Carbon (PC; charcoal, black carbon) production is estimated at 50–270 Tg/yr (Kuhlbusch and Crutzen, 1995), with >90% of this remaining on the ground after the fire (Kuhlbusch et al., 1996). It has been demonstrated that, once formed, PC can persist in the environment for tens of thousands of years (Bird and Cali, 1998) and both modeling (Lehmann et al., 2008) and incubation studies (Kuzyakov et al., 2009) generally infer turnover times for PC of centuries to millennia. In contrast to the view that turnover times for PC are at least centennial, field studies have demonstrated almost complete loss of PC from tropical savanna soils protected from fire on decadal timescales (Bird et al., 1999). In an experiment in frequently burnt savanna in Kruger National Park, Kuhlbusch et al. (1996) 'looked carefully at the soil prior to the fire for any black carbon particles from previous fires, but could find only very few', providing anecdotal evidence for the rapid loss of PC from savanna landscapes. Likewise, Alexis et al. (2007) found no charcoal in surface litter samples in their field site that had been burnt 11 years prior to their experimental burn which produced surface litter containing 18% charcoal. Masiello and Druffel (2003) used a mass balance approach to demonstrate that a substantial fraction of the PC produced annually from biomass burning must be re-mineralized, or the accumulation of PC in the environment over time would be sufficient to perturb global atmospheric oxygen levels. These observations suggest a 'missing sink' for PC and therefore a substantial gap in our understanding of the processes by which PC must be re-mineralized in the environment.

Tropical savannas cover about one-sixth of the earth's land surface and account for over a quarter of primary production of terrestrial vegetation (Grace et al., 2006). Their relevance to the global PC budget is underscored by the fact that these ecosystems are subject to regular fires of varying intensity due to the combination of sufficient seasonal rainfall to generate significant biomass, plus an extended dry season that cures a high fuel load. Mouillot and Field (2005) estimate that 86% of annual global burnt area is located in tropical savanna/grassland regions and Kuhlbusch et al. (1996) estimated that savanna fires contribute 10–26 Tg (4–52%) to global annual PC production. Forbes et al. (2006) calculated a PC conversion rate from biomass of below 3% for savanna and grassland ecosystems. Savannas store larger amounts of recalcitrant carbon in the soil compared to tropical forest ecosystems as a result of frequent fire events that promote the formation of PC (Saiz et al., 2012). Indeed, PC can constitute a significant fraction of

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the total soil carbon pool in these ecosystems, and can compare well and even significantly exceed PC storage rates observed in non-tropical grasslands, boreal forests, and other fire-prone natural environments (Lehmann et al., 2008; Rodionov et al., 2010; Saiz et al., 2012; Skjemstad et al., 1999). Tropical savannas are therefore the environments in which a substantial amount of biomass is regularly consumed by fire, where a substantial fraction of global PC production occurs, and where a substantial fraction of PC must be re-mineralized.

The production of charcoal from grass-derived biomass in tropical savannas may be significant given the high re-occurrence of fires consuming this very abundant and easy-to-combust material (Grace et al., 2006). Cachier et al. (1985) have shown that about 75% of the total aerosol particle production during combustion of tropical savanna vegetation derives from C4 grass material. Moreover, there is also evidence showing that a significant proportion of all charcoal present in the soil of tropical savannas is finely divided (Bird et al., 1999; Skjemstad et al., 1999), which suggests that PC is mainly derived from precursor biomass capable of resulting in small char particles (e.g. grasses) and that large PC fragments get progressively comminuted to small sizes. A recent study by Nocentini et al. (2010) has also shown that physically distinct charcoal particles have different chemical composition implying different turnover behavior in soil, with fine particles being most probably degraded faster than coarse ones. Moreover, fine PC may well be removed from its site of production by wind or water (Bird and Cali, 1998; Kuhlbusch and Crutzen, 1995), but this constitutes remobilization of PC, not re-mineralization, and PC production is greater than the rate of burial in the ocean (Hedges and Keil, 1995). Coarse PC derived from woody biomass represents a substantial component of total PC that will potentially remain in situ, and therefore must be re-mineralized in situ. If this material is not as inert as currently suggested then, it might conceivably be re-mineralized over time by any, or all, of microbial respiration, photochemical degradation, or re-combustion by subsequent fires. A fraction of this total coarse PC may also get comminuted by physico-chemical degradation and moved as fine particles or in solution into the soil and potentially on into rivers and ultimately the ocean (Bird et al., 1999).

The aim of this study is to specifically assess whether charcoal re-combustion by subsequent fires in tropical savannas represents a significant mechanism by which PC is re-mineralized. Re-ignition of surface PC by subsequent fires has been suggested as one of the factors explaining charcoal disappearance in fire-prone boreal ecosystems and non-tropical grasslands (Czimczik et al., 2005; Ohlson and Tryterud, 2000; Preston and Schmidt, 2006; Rodionov et al., 2010). Moreover, the possibility that re-combustion may play a role in tropical systems has also been suggested (Bird et al., 2000; Czimczik and Masiello, 2007; Grace et al., 2006). However, to-date no field study has tested the degree to which re-combustion in subsequent fires may provide an explanation of the 'missing sink' for PC. We conducted duplicated controlled fire experiments at two tropical savanna sites under conditions in which the intensity of the fire, and hence the likelihood for PC re-ignition and combustion were maximized. We also tested the influence of the size of charcoal fragments on re-combustion probability.

2. Materials and methods

2.1. Site description

A total of four plots were laid out in two open savanna woodlands subject to regular prescribed fires typically occurring at four-year intervals in Far North Queensland (Australia). Two of these plots were established in Davies Creek National Park (DCR; 17.021° S, 145.584° E), while the other two were located in Brooklyn Nature Refuge (BRK; 16.586° S, 145.155° E). Tree canopy cover determined by means of site-specific allometric equations and visual estimates was 55 and 40% for DCR and BRK respectively. The biomass present in the fire trial areas was mainly composed of a grass layer dominating over sparse Eucalyptus and Acacia tree seedlings with variable amounts of coarse woody debris and leaf litter. The most abundant grass species were *Themeda australis*, *Imperata cylindrica* and *Heteropogon contortus*. Mean understorey biomass was determined by vegetation clippings and litter collection at eight one-square meter locations at each study site. An average of 992.0 (284.5) and 771.3 (127.2) g dry mass/m^2, determined from 8 × 1 m^2 plots at each site, was observed for DCR and BRK, respectively; errors in brackets are standard deviations of the mean.

2.2. Characteristics and set up of the charcoal fragments

Acacia aneura charcoal pieces that were produced during a prescribed fire to clear land for cattle in central Queensland in 1998 and subjected to 'in situ' natural weathering for over ten years were used in the experiment. Wood density of the species is 1.0 g/cm^3 and the resultant apparent density of the charcoal fragments was ~0.5 g/cm^3. The charcoal was produced at ~700 °C with an elemental composition of 78.2% C, 2.3% H, 13.8% O, and 5.5% ash, with a single point BET surface area of 398 m^2/g. For further information about charcoal characteristics and methods used for their determination, please refer to Zimmermann et al. (2012). Charcoal fragments were cleaned of any dirt or debris, and size-classified by means of dry sieving. We used meshes of 1 and 0.5 cm which resulted in three separate size classes: <0.5, 0.5–1.0, and >1 cm. Charcoal pieces within each size class were handpicked and selected to be of approximately the same average size (0.25, 0.75 and 1.5 cm) to make results readily comparable. The charcoal fragments were placed in an oven at 105 °C for 24 h and then weighed.

Fire plots were delimited by firebreaks resulting in 10 × 15 m areas over which pieces of charcoal were carefully placed along a 0.1 × 0.1 m grid set out at least 3 m away from any of the plot boundaries. Previous research has shown that in ecosystems where grass is the main fuel, the size of the plot is of minor importance with regard to maximum measured fire temperatures (Stinson and Wright, 1969). The grid was initially set up on the ground so as to mark the exact potential locations where the fragments could be deployed. Charcoal fragments were randomly allocated across the plot in the BRK experiment (random cells within the grid), while in the later experiment conducted in DCR, we employed a stratified protocol ensuring each size-class of charcoal was placed both in close proximity to, and midway between grass tussocks in order to test whether distance to the fuel was a significant factor affecting re-combustion. We took note of all used cells within the grid.

We chose to deploy a greater number of smaller pieces of charcoal as they are more abundant than larger particles in nature. Moreover, we hypothesized that smaller fragments would be more prone to combustion than larger fragments due to their larger surface to mass ratio. Accordingly, we allocated 1, 3 and 5 pieces of charcoal from the >1, 0.5–1 and <0.5 cm size categories respectively at each selected location. A total of 264 pieces of charcoal were individually monitored over the four burns (Table 1). Always taking the centre of the grid cell as reference, individual large samples (>1 cm) were arranged in the middle of the grid location. The three medium size fragments (0.5–1 cm) were laid out as a triangle, while the five fragments corresponding to the smallest size category (<0.5 cm) were set up displaying a cross. Separation between fragments within the same location was 2.0 cm. The geometrical layouts of the fragments prior to the fire were used to facilitate their relocation after the fire. We made sure no native charcoal fragments were in the immediate vicinity to ours to avoid any post collection mixing-up. After all samples were on place, the grid was offset by an accurate 2 m downwind distance. The exact position of the grid's four corners at the offset location was distinctively marked using colored pegs, which was followed by the retrieval of the grid previous to the fire. Successive trials repositioning the grid back into the original charcoal locations, demonstrated the goodness of such approach as a means to accurately relocate all the fragments after the fire.