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Disentangling effects of key coarse woody debris fuel properties on its combustion, consumption and carbon gas emissions during experimental laboratory fire

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ABSTRACT

Coarse woody debris is a key terrestrial carbon pool, and its turnover through fire plays a fundamental role in global carbon cycling. Coarse dead wood fuel properties, which vary between tree species and wood decay stages, might affect its combustion, consumption and carbon gas emissions during fire, either directly or indirectly through interacting with moisture or ground-wood contact.

Using controlled laboratory burns, we tried to disentangle the effects of multiple biotic and abiotic factors: tree species (one conifer and three hard wood species), wood decay stages, moisture content, and ground-wood contact on coarse wood combustion, consumption, and CO_2 and CO emissions during fire. Wood density was measured for all samples.

We found that, compared to the other tested factors, wood decay stages acted as a predominant positive driver increasing coarse wood flammability and associated CO_2 and CO emissions during fire. Wood moisture content (30 versus 7%) moderately inhibited wood flammability with slight interaction with wood decay effects. Wood decay effects can be mainly attributed to the decreasing wood density as wood becomes more decomposed.

Our experimental data provides useful information for how several wood properties, especially moisture content and wood decay stages, with wood density as the key underlying trait, together drive coarse wood carbon turnover through fire to the atmosphere. Our results will help to improve the predictive power of global vegetation climate models on dead wood turnover and its feedback to climate.

1. Introduction

Coarse woody debris (CWD) is recognized as an important carbon pool because of its large storage and long residence time in nature. Of the ~360 Pg carbon contained in the world's forest biomass, 10–20% is present as CWD (Dixon et al., 1994, Delaney et al., 1998, Brown, 2002, Goodale et al., 2002, Cornwell et al., 2009), which generally has a long residence time of years to centuries (Cornelissen et al., 2012, Russell et al., 2014). So understanding coarse wood carbon turnover is fundamental to global carbon cycling (Harmon et al., 1986, Cornwell et al., 2009, Brovkin et al., 2012, Cornelissen et al., 2012).

Biological decomposition and fire are two alternative pathways for coarse wood carbon turnover (Cornwell et al., 2009, Cornelissen et al., 2012, 2017). Compared to the gradual biological decomposition process, fire can induce a pulse-wise release of the coarse wood carbon to the atmosphere (Rabelo et al., 2004, Hyde et al., 2011, Cornelissen et al., 2012, Volkova and Weston, 2013, Cornelissen et al., 2017).

In order for fires to occur, three conditions must be met. The environmental (weather) conditions must be such that the fuel is dry enough to burn, some source of ignition must be present, and there must be sufficient fuel (Bond and van Wilgen, 1996). Coarse dead wood fuel properties, including dead wood and bark chemistry and structure and their interactions with wood moisture content, can vary considerably between tree species and wood decay stages. Those variations are also very important to determine whether, and how a piece of dead wood will be consumed by fire. Wood with high moisture content requires more energy to drive water from wood during the heat-up and drying phases before ignition (Tillman, 1981, Hyde et al., 2011). Even after ignition, high moisture content catalyzes charring reactions directly or indirectly by decreasing the flaming temperature (Babrauskas,

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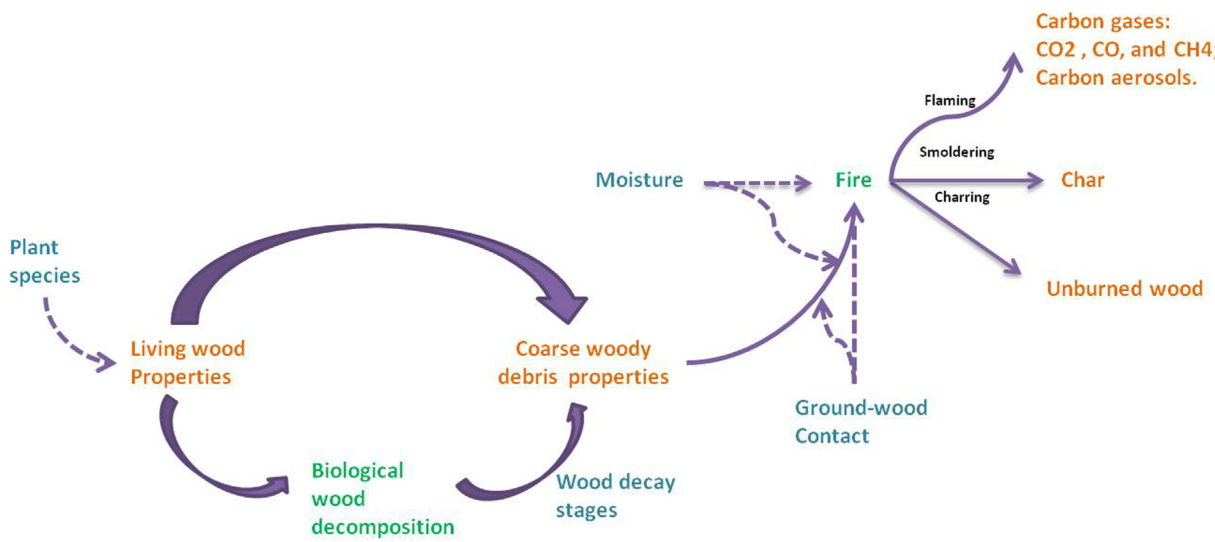

Fig. 1. The conceptual framework showing multiple drivers of carbon fluxes from coarse woody debris to the atmosphere. We divided living wood, coarse woody debris, carbon gases, char, and unburned wood as different *carbon pools*; biological wood decomposition and fire as *carbon release pathways* through which the organic wood carbon turns over; plant species and wood decay stages as the *biotic drivers*, moisture and ground-wood contact as the *abiotic drivers* of the carbon flux.

2006, Cornwell et al., 2009, Hyde et al., 2011). Wood density, porosity, diameter, surface area-to-volume ratio can influence the oxygen availability, heat conductivity during burning (Ohlemiller, 1985, Carvalho et al., 2002, Thunman and Leckner, 2002, de Souza Costa and Sandberg, 2004, Rabelo et al., 2004, Rein, 2009, Hyde et al., 2011, Hyde et al., 2012, Zhao et al., 2014). Wood lignin and cellulose content may change wood combustion chemistry (Tillman, 1981, Dobry et al., 1986, White, 1987, Knoll et al., 1993, Cornwell et al., 2009, Demirbas and Demirbas, 2009). Wood structure and chemistry can also influence coarse wood combustion indirectly through changing its water dynamics: water holding capacity and water losing rate (Zhao et al., 2014). The degree of ground-wood contact (above/on the ground surface), which is determined by the complex interaction between tree architecture, tree death pathways and forest floor surface structure, might also affect wood combustion through changing oxygen availability and the surrounding temperature during fire (Rabelo et al., 2004, Cornwell et al., 2009, Hyde et al., 2011).

Dead wood properties, which are mainly determined by living wood traits and their after-life effects on biological wood decomposition, vary between plant species and wood decay stages (Harmon et al., 1986, Swenson and Enquist, 2007, Chave et al., 2009, Cornwell et al., 2009, Cornelissen et al., 2012, Freschet et al., 2012). Usually gymnosperms have lower living wood density than angiosperms, mostly because gymnosperms have relative higher abundance of conduit cells per stem cross-section area. While dead wood of gymnosperms usually decomposes slower than that of angiosperms, which presumably can be explained by the lower lignin concentration and lower lignin/N ratio of angiosperm wood promoting the activity of wood decomposing organisms (Swenson and Enquist, 2007, Chave et al., 2009, Cornwell et al., 2009, Weedon et al., 2009, Cornelissen et al., 2012). As wood decays, generally its density and porosity increase, the lignin to cellulose ratio changes, and the overall shape may also change as structural integrity is lost (Cornwell et al., 2009, Hyde et al., 2011, Cornelissen et al., 2012, Hyde et al., 2012, Zhao et al., 2014). Those variations in wood structure and chemistry properties among plant species and wood decay stages might change wood flammability (Hyde et al., 2011, Hyde et al., 2012, Zhao et al., 2014). Here we specify wood flammability in terms of ignitability (ease of ignition), sustainability (fire duration), combustibility (fire velocity or intensity), and consumability (the amount of fuel combusted) (Anderson, 1970).

During combustion, wood organic carbon (CH_2O) is released to the atmosphere as carbon dioxide (CO_2), carbon monoxide (CO), methane (CH_4), other hydrocarbons, and elemental C aerosols (Bertschi et al., 2003, Cornwell et al., 2009, Ottmar, 2014). The composition and concentration of these carbon gases and aerosols in the atmosphere directly influence air quality in the short term, while they influence global climate in the long term through their radiative force (Andreae and Merlet, 2001, Page et al., 2002, van der Werf et al., 2003, van der Werf et al., 2006, de Groot et al., 2007, Bonnicksen, 2008, van der Werf et al., 2009, van der Werf et al., 2010, Fernandes and Loureiro, 2013, Urbanski, 2013, Ottmar, 2014). Total fire carbon emissions are roughly 20% of total fossil fuel carbon emissions, but most fire CO_2 emissions are compensated for by regrowth (van der Werf et al., 2010). These fire emisisons are uncertain, and a better understanding of coarse wood fire dynamics may help in lowering uncertainties in these estimates. Carbon emission through coarse wood combustion can contribute a significant portion to carbon emission during fire. Because of its relatively slow combustion rate, the carbon emission through coarse wood to fire is usually indirectly estimated by burned area, fuel load and fuel burning completeness for regional or global scale emstimation fire emissions (Bertschi et al., 2003, Ottmar, 2014). However, for prediciting and modeling carbon emissions based on ground-based measurements of fuel properties and fire behavior, it is important to take into account and quantify the role of charring through smouldering. In this common alternative pathway for complete combustion, especially at lower fire temperatures, mass loss due to fire may not scale linearly with carbon loss, as hydrogen and oxygen are lost in this process while carbon gets more concentrated.

To disentangle effects of key drivers of coarse woody debris properties on its carbon turnover through fire to the atmosphere, and to compare the magnitudes of those effects, we tested separate and interactive effects of plant species, wood decay stages, and moisture content at different extents of ground-wood contact on coarse wood flammability and carbon gas emissions (Fig. 1) for four widespread temperate and boreal forest tree species in a fire laboratory. Specifically the following research questions are addressed:

(1) How do plant species, wood decay stages and their interaction influence coarse wood flammability and carbon gas (CO_2 and CO) emissions during fire? (2) To what extent do the relationships under (1) differ between air-dry (7% moisture content) and moist (30% moisture content) dead wood? (3) Is there a significant first order effect of ground-wood contact on flammability? (4) Is there a one to one linear relationship between mass loss predicted and measured carbon emissions?