Forest Ecology and Management 400 (2017) 475–484

Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

Tree species identity in high-latitude forests determines fire spread through fuel ladders from branches to soil and *vice versa*

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ARTICLE INFO

Article history:
Received 11 January 2017
Received in revised form 7 June 2017
Accepted 8 June 2017
Available online 26 June 2017

Keywords:
Fuel type interaction
Soil ignition
Boreal forest
Species community
Combustion

ABSTRACT

Peat fires in boreal and tundra regions can potentially cause a high CO_2 release, because of their large soil carbon stocks. Under current and future climate warming the frequency and intensity of droughts are increasing and will cause the plant community and organic soil to become more susceptible to fire. The organic soil consumption by fire is commonly used as a proxy for fire severity and is a large source of carbon release. However, the role of organic soils in both above- and belowground fire behavior has only rarely been studied. In this study we collected soil and branches from *Betula pubescens, Pinus sylvestris* and *Picea abies/obovata* from the taiga/tundra ecotone across a large spatial scale. In laboratory fire experiments we burned different fuel type combinations to examine the fire spread through fuel ladders both from branches to soil and *vice versa*. We found that the tree species identity influences the fire spread from branches to soil and *vice versa*. The combination of chemical and structural plant traits could explain the stronger interaction between soil and coniferous spruce and pine fuels in a fire ladder compared to the deciduous birch. Therefore, total carbon emission from a boreal forest fire may not only depend on burned plant fuel, but also on the species-specific potential of the trees to ignite the soil. Carbon emission models and forest management could be improved if not only the aboveground plant fuel consumption is considered, but also the interaction between fuels in a fuel ladder and the probability of soil ignition by a forest crown fire and *vice versa*.

1. Introduction

Wildfires can have a tremendous impact on ecosystems. Future fire regimes will change because global temperature will continue to increase during this century (Price and Rind, 1994; Flannigan et al., 2000; IPCC, 2013). In particular at higher latitudes temperatures will increase more than at lower latitudes (Collins et al., 2013). The changing climate at higher latitudes may cause shifts in tree species composition. Currently the forest-tundra ecotone of Northern Fennoscandia is dominated by downy birch (*Betula pubescens*) and its location is affected by temperature, local grazing by deer and moose and interactions with shrubs (Cairns and Moen, 2004; Karlsson et al., 2005; Grau et al., 2012). Sporadically, individuals or groups of pine (*Pinus sylvestris*) and spruce (*Picea abies/obovata* or hybrids) are observed. Such outposts of these species may benefit from future climate change and expand northwards and therewith change the local species composition. The distribution of *Picea*, *Pinus* and *Betula* in Northern Europe has shifted over the past millennia and may continue to change this century (Huntley, 1990). Precipitation plays a crucial role in the distribution of tree species, but future prediction about precipitation have a high uncertainty and therefore the future species composition cannot be accurately predicted (Badeck et al., 2001). Models suggest that climate warming can cause the distribution of spruce and pine to shift north-east (Sykes and Prentice, 1996). Comparable shifts in composition of these tree genera may occur in Siberia and perhaps other cold-climate forest areas. Due to species- or genus-specific differences in flammability, such changes in species distribution may change the fire regime and therewith affect ecosystem responses including their carbon balance. Thus, climate change may not only directly affect fire regimes in the tundra-taiga ecotones due to prolonged droughts, but also indirectly through changes in tree species composition.

In general, the moisture content, 3-D arrangement and mass of the fuel are the most important drivers of the fire spread and intensity of a forest fire (Rothermel, 1972; Rowe and Scotter, 1973), while fuel chemical composition and surface texture may also be important. These properties make that, at given climatic conditions, fire regimes in coniferous forests are expected to be more severe than in broad-leaved forests (Hely et al., 2001). Two important fire behavior parameters, the fire front intensity and spread

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http://dx.doi.org/10.1016/j.foreco.2017.06.023
0378-1127/© 2017 The Authors. Published by Elsevier B.V.

rate, are predicted to be higher in coniferous forests. On the other hand, it has been reported that a broadleaved species ignited faster than a needle leaved species (Alessio et al., 2008). A higher fuel load in coniferous forests may be expected, because along the succession of a boreal forest, the biomass and relative abundance of conifers increase simultaneously (Bergeron and Dansereau, 1993; Goulden et al., 2011). Also, leaf and woody litter of conifers is generally decomposed more slowly than that of broad-leaf tree species (Pietsch et al., 2014), resulting in soils with deeper and carbon-richer organic horizons and stronger litter accumulation on the soil surface. Furthermore, broad leaves generally contain more water than needles (Rowe and Scotter, 1973). The tree species composition therefore determines, in part, the fire intensity and severity in boreal forests.

Fire severity, i.e. fuel consumption, in boreal forests is not only based on the combustion of aboveground fuels, but also of the soil organic carbon (SOC). Higher latitude soils can contain large amounts of organic carbon and fire is a fast pathway to release that carbon into the atmosphere (Kasischke et al., 1995). Under dry conditions and severe fire intensity the soil carbon can ignite and combust in a smoldering state. Large smoldering peat fires are well known for the release of tremendous amounts of carbon (Page et al., 2002; Mack et al., 2011). The amount of carbon released from fires depends on the fuel composition and fire behavior in the system (Boby et al., 2010). A change in tree composition, like in Northern Europe, can thus change the aboveground fire behavior and thereby the combustion and release of soil organic carbon.

Changes in species composition can also affect the interaction between aboveground plant species and with that the fire behavior and carbon emission (Rossiter et al., 2003; Brooks et al., 2004; McGranahan et al., 2013; Zhao et al., 2016). In contrast with the elaborate attention given to aboveground fuels, the role of soil organic carbon in fire behavior, when considered at all, is usually only used as proxy of fire severity (Boby et al., 2010; Parson et al., 2010). This is a serious omission as the organic carbon that is stored in the top soil layer could play an important role in fire behavior and carbon emission, because organic soils can have a high carbon density and smolder persistently (Rein, 2013). However, while interactions between different aboveground fuel types are known to cause changes in fire behavior (de Magalhaes and Schwilk, 2012; van Altena et al., 2012; Blauw et al., 2015), interactive effects of below- and aboveground fuels on fire behavior have rarely been studied. Empirical studies about the role of interactions between soil organic matter and aboveground dead or living biomass on fire behavior are necessary to understand the full scope of fire behavior and carbon emission from fires in ecosystems with soils rich in organic carbon.

The involvement of soil organic carbon in fire depends on ladder fuels, like low-hanging tree branches, shrubs, tree saplings and litter, that can support the fire from spreading from one vertical fuel layer to another (Scott and Reinhardt, 2001). In this paper we focus specifically on the forest fire ladders close to the surface, i.e. the interface that allow the fire to spread from low-hanging tree branches to soil and *vice versa* (Fig. 1, right side; (Schwilk and Ackerly, 2001). While there is much evidence for the importance of fuel ladders for fire spread from soil to branches (Bradley et al., 1992; Arno et al., 1995), very little is known about the importance of low branches in transferring fire into the soil, even though 'spotting' through burning branches being propelled to the surface is a well-known phenomenon (Tarifa et al., 1965; Albini et al., 2012).

Such fire ladders are more likely at higher latitudes, near the forest-tundra ecotone, because in these open forests self-pruning of lower branches is strongly reduced, leaving many branches that almost or entirely touch the soil surface (Fig. 1, left side). However, not only the position but also the properties of these potential fuels determine the success of a fire ladder. Plant traits, like, bulk density, concentrations of carbon, terpenes and other secondary compounds can be important for the ignitability and sustainability (Ormeno et al., 2009; de Magalhaes and Schwilk, 2012; Grootemaat et al., 2015; Pausas et al., 2016). Different fuel types, like leaves, branches and soil organic matter, have distinct trait values and the interaction between these fuels likely determines the above- and belowground fire behavior.

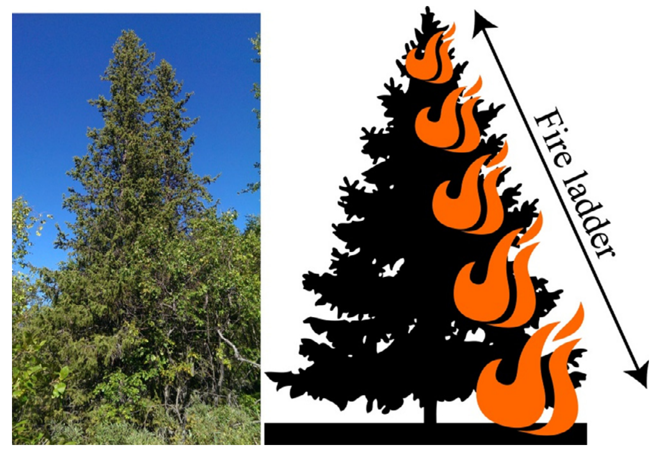

Fig. 1. Left: A true image from the field showing a fuel ladder in N Sweden. Right: Cartoon example of a fire ladder from branches to soil and *vice versa*. Photo by the authors.

Fire spread, via a fire ladder, is an important fire element that mainly depends on the ignitability of the fuels and temperature of the heat source. The tree species identity, i.e. a unique set of trait values, may be crucial for the success and efficiency of the fire ladder from branches to soil and *vice versa*. Thus, we hypothesize that variation or changes in tree species composition, via the trait-dependent interactions between fuels, determine the functioning of the fire ladder.

To test this main hypothesis we examined how the identity of different tree genera predominant at higher latitudes determines the fire behavior in both directions of a fire ladder, and therefore the specific hypotheses of this study were:

1. that both the soil and plant fuel ignition will be faster and fires more intense in fuel ladders involving branches of coniferous trees compared to those of broad-leaved trees.
2. that with increasing distance between the fuel types, i.e. branches and soil, the ignition and fire intensity should decrease in both directions of the fuel ladder.

To test these specific hypotheses, we combined field sampling of branches and soil material from *Betula* dominated stands with sparse *Picea* and/or *Pinus* individuals, along an extensive geographical gradient among distant sites in Northern Fennoscandia. We then carried out experimental fuel ladder burns in the lab from branches to soil and *vice versa*. As such, this unique and truly replicated design represents trait and soil variation across Northern Fennoscandia, with implications also for high latitude forests elsewhere.

2. Methods

2.1. Study sites and sampling

In Northern Sweden and Finland we searched at the tundra/-taiga ecotone for *Betula pubescens* Ehrh. dominated forest stands