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Direct and longer-term carbon emissions from arctic-boreal fires: A short review of recent advances

Sander Veraverbeke[1], Clement J. F. Delcourt[1], Elena Kukavskaya[2], Michelle Mack[3], Xanthe Walker[3], Thomas Hessilt[1], Brendan Rogers[4] and Rebecca C. Scholten[1]

Abstract

Increases in arctic-boreal fires can switch these biomes from a long-term carbon (C) sink to a source of atmospheric C through direct fire emissions and longer-term emissions from soil respiration. We here review advances made by the arctic-boreal fire science community over the last three years. Landscapes of intermediate drainage tend to experience the highest C combustion, dominated by soil C emissions, because of relatively thick and periodically dry organic soils. These landscapes may also induce a climate warming feedback through combustion and postfire respiration of legacy C, including from permafrost thaw and degradation. Legacy C is soil C that had escaped burning in the previous fire. Data shortages from fires in tundra ecosystems and Eurasian boreal forests limit our understanding of C emissions from arctic-boreal fires. Interactions between fire, topography, vegetation, soil, and permafrost need to be considered when estimating climate feedbacks of arctic-boreal fires.

Addresses

[1] Faculty of Science, Vrije Universiteit Amsterdam, Amsterdam, the Netherlands

[2] V.N. Sukachev Institute of Forest, Siberian Branch of the Russian Academy of Sciences – Separate Subdivision of the FRC KSC SB RAS, Krasnoyarsk, Russia

[3] Center for Ecosystem Science and Society, Northern Arizona University, Flagstaff, AZ, USA

[4] Woodwell Climate Research Center, Falmouth, MA, USA

Corresponding author: Veraverbeke, Sander (s.s.n.veraverbeke@vu.nl)

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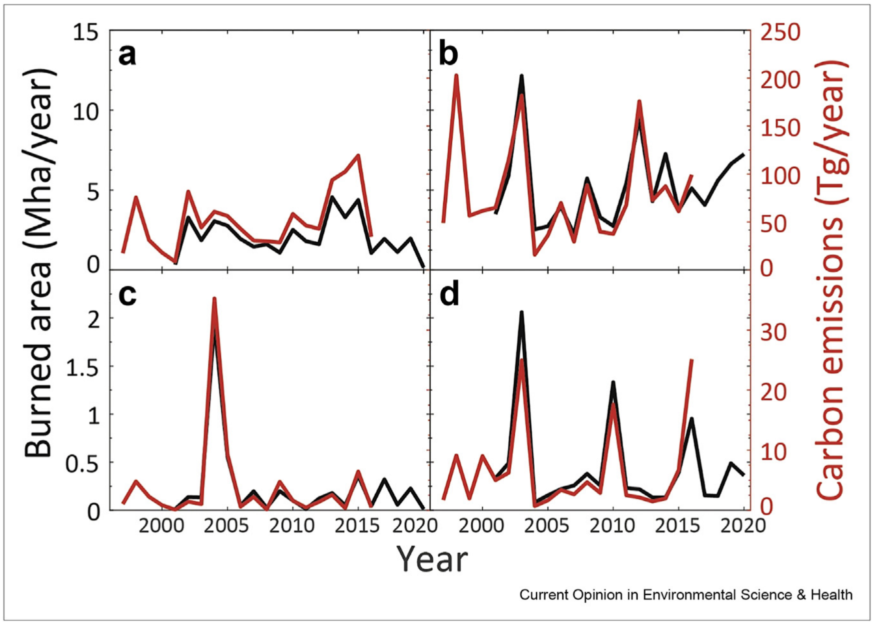
Arctic, Boreal, Carbon, Fire, Permafrost, Tundra.

1. Introduction

Arctic-boreal ecosystems have been a persistent long-term carbon (C) sink, yet increases in fire frequency and severity threaten this sink [1,2]. Arctic-boreal fires emit on average 142 Tg C per year, which represents 7.0% of the global carbon emissions from fires (for definitions of regions and datasets, see the appendix). Despite the relatively high contribution to global fire emissions, arctic-boreal fires burn on average 8.0 Mha per year, which represents only 1.6% of the global burned area. The relatively high contribution of arctic-boreal fires to global C emissions from fires relative to their burned area shows that they have high C combustion, or area-normalized C emissions [3]. The majority, 70.7%, of the arctic-boreal burned area is located on the Eurasian continent, whereas the remaining 29.3% occurs on the North American continent. Fires occurring in forests comprise 91.5% of the arctic-boreal burned area vs. 8.5% in tundra. Both burned area and carbon emissions are highly variable between years for forest and tundra on both continents (Figure 1).

The majority of C stored in arctic-boreal ecosystems is belowground in C-rich peatlands and permafrost soils [4]. Burning in these landscapes can therefore result in high C emissions [5,6]. The large majority of arctic-boreal burned area occurs in landscapes with peat occurrence; 2.3% of the arctic-boreal burned area is in peat-dominated landscapes (peat coverage $>$ 50%) and 96.9% of the arctic-boreal burned area is in landscape with peat prevalence (0% $<$ peat coverage $\leq$ 50%). In addition to direct C emissions from fires, arctic-boreal fires may impact soil-atmosphere C fluxes for decades after the fire [7]. Fires remove part of the insulating organic layer and moss, which leads to thickening of the seasonally thawed active layer above the permafrost [8]. This can result in multidecadal changes in soil respiration of carbon dioxide (CO_2) and methane (CH_4) [7]. A large fraction, 42.2%, of the arctic-boreal burned area occurs in continuous permafrost terrain, 17.3% in discontinuous permafrost terrain, 36.9% in sporadic and isolated permafrost landscapes 3.6% in landscapes without permafrost (Figure 2).

Figure 1



Annual burned area and carbon emissions from boreal forest fires in North America (**a**) and Eurasia (**b**), and tundra fires in North America (**c**) and Eurasia (**d**) (for definitions of regions and data sets, see the appendix). Note that the y-axes are scaled differently for the boreal forest and tundra plots.

The occurrence of arctic-boreal fires in C-rich peatlands and permafrost landscapes demonstrates the vulnerability of arctic-boreal soil C to fire. Soil C can be emitted to the atmosphere by both the direct fire emissions and by longer-term soil emissions after fire. C emissions can be part of a relatively short-term C cycle, defined by a given ecosystem's fire return interval. In this case, and as long as the fire return interval is stable, C assimilated by the ecosystem during the last fire-free interval is emitted and the system is either C-neutral or a C sink [1]. Alternatively, if fires become more frequent or severe, C that had escaped the previous fire may be emitted. This legacy C is part of a longer-term C cycle [1]. In contrast to the emissions of short-cycling C, the emissions of legacy C have a net climate warming effect.

In this opinion, we review the last three years' progress in our understanding of C emissions from arctic-boreal fires. We first focus on the direct C emissions. We then continue by summarizing recent progress in our mechanistic understanding of longer-term postfire C emissions. We conclude with summarizing the main findings and by formulating research priorities.

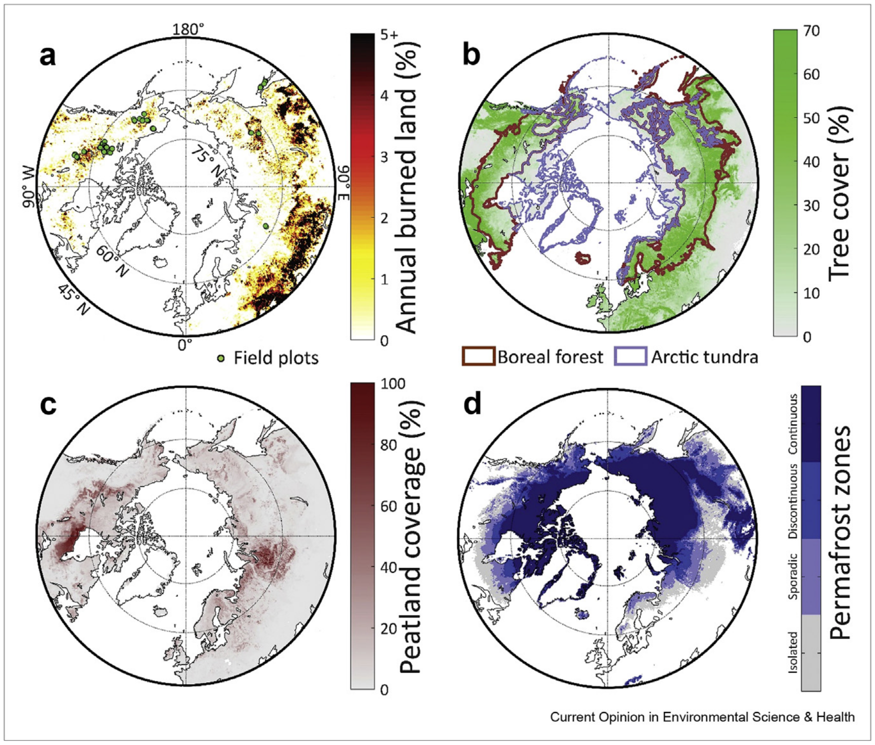
Direct carbon emissions from arctic-boreal fires

We discuss recent progress on the quantification and understanding of direct fire C emissions separately for the North American and Eurasian continents given their different fire behavior, and thus potentially emissions characteristics too, that results from disparities in the dominant boreal tree species between the continents [9]. In boreal North America, fire embracers, notably black spruce (*Picea mariana* Mill.) and jack pine (*Pinus banksiana* Lamb.), dominate, resulting in stand-replacing high intensity crown fires [9]. By contrast, fire resisters and avoiders prevail in boreal Eurasia, notably Larix species (*Larix sibirica* Ledeb., *Larix gmelinii* Rupr. and *Larix cajanderii* Mayr.), Scots pine (*Pinus sylvestris* L.), and Siberian pine (*Pinus sibirica* Du Tour). This frequently results in low intensity surface fires, in which trees often survive [9].

North America

Average C combustion from field measurements in arctic-boreal North America ranges between 1.99 kg C m^{-2} (sd = 1.31 kg C m^{-2}) for tundra ecosystems and 3.55 kg C m^{-2} (sd = 1.71 kg C m^{-2}) for black spruce forest (Figure 3). The majority of C emissions stem from belowground pools, for example on average 89.9% in black spruce forest. Combustion in black spruce forests is considerably higher than that in forests dominated by jack pine or deciduous trees, where on average 2.45 kg C m^{-2} (sd = 1.91 kg C m^{-2}) is combusted. The majority of fires in boreal North America occurs in black spruce stands, and landscape gradients in black spruce dominance are dictated by topographic differences in drainage and fire-driven succession [5,6]. Black spruce thrives in wet lowlands and intermediate drainage positions that are wet for

Figure 2



Circumpolar maps of annual burned land (**a**), tree cover and biome boundaries (**b**), peatland coverage (**c**), and permafrost zones (**d**). (for more information on the gridded datasets, biome boundaries and field measurements, see the appendix).

most of the year. Black spruce forest typically feature thick organic soils, of which the top layer can dry out during the fire season for stands at intermediate drainage positions. Well-drained uplands, often dominated by white spruce, jack pine or deciduous trees, are characterized by more shallow organic soils. Drainage conditions strongly drive carbon combustion in boreal North America [6]. Perennially wet lowland sites store large amounts of C in organic soils, yet seldom burn. In well-drained upland sites, fires often consume the entire, yet shallow, organic soil. Sites at intermediate drainage positions experience the highest combustion owing to their combined fuel availability and periodic drying during the fire season [6]. Intermediate landscape positions are also prone to prolonged smoldering in organic soils [10], which may result in the release of legacy C, especially in young forests [1].

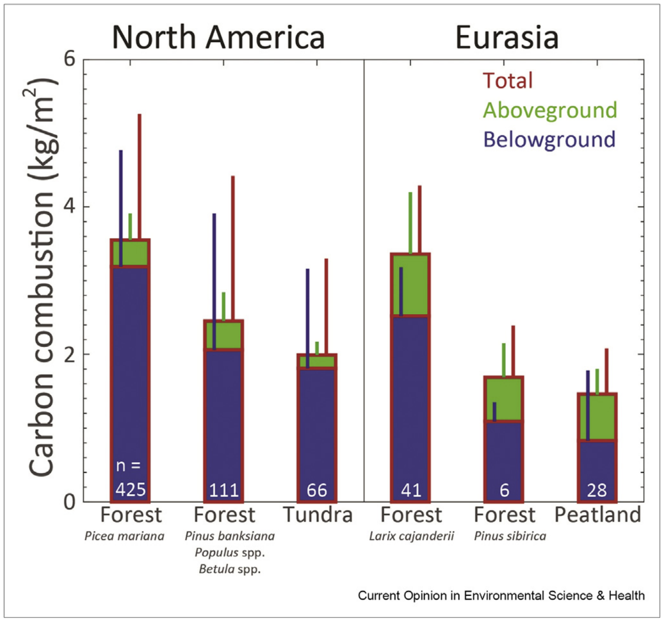
Latitudinal differences in solar insolation are another major control on boreal forest composition and C combustion. Boreal forest stands in southern Canada tend to be more productive, have higher aboveground fuel loads and burn more frequently than forest stands in northern Canada [5,11]. Total combustion remains relatively similar across a latitudinal gradient, yet aboveground combustion is comparatively more important in southern boreal forests compared with northern stands [5,6,11]. Compound effects of timber harvest followed by fire resulted in slightly higher combustion rates, driven by higher fuel availability because of faster recovery of aboveground C pools after harvest compared with natural forest recovery [11]. Dieleman et al. [11] suggested that the current fire regime and ecosystem structure of southern boreal forest may be an analog for the future northern boreal forest. If such an ecosystem shift occurs, this would reduce C storage in the northern boreal forest belowground pools [12].

C combustion measurements from tundra fires are scarce (Figure 3), yet can be substantial owing to the availability of C-rich organic soils. Mack et al. [13] reported relatively constant burn depths and C losses across their measurements in the large 2007 Anaktuvuk River fire scar on Alaska's North Slope. Large variations in prefire organic soil depth had relatively little influence on burn depth and C losses, which was mediated by horizontal layering of organic soils influencing its bulk density, particle size, and hydraulic conductivity.

Eurasia

Despite the large variability in ecosystems and fire effects in Eurasia, the number of available field measurements on C combustion from wildfires in arctic-boreal Eurasia is roughly an order of magnitude smaller compared with arctic-boreal North America (Figure 3). Average combustion estimates of

Figure 3



Field-measured carbon combustion from wildfires in arctic-boreal ecosystems of North America and Eurasia. Belowground consumption includes combustion of organic soils, litter and moss. Aboveground consumption includes combustion of woody debris, grasses, shrubs, and trees. Total consumption is the sum of belowground and aboveground consumption (for more information on the field datasets, see the appendix). The bar plots represent the means and the error bars the standard deviations.

1.69 kg C m^{-2} (sd = 0.70 kg C m^{-2}) in Siberian pine forest [14] and 1.45 kg C m^{-2} (sd = 0.63 kg C m^{-2}) in forested peatland [15] from surface fires are relatively low. This is in accordance with satellite-inferred reductions in fire radiative power, a proxy of instantaneous fire emissions, in boreal Eurasia compared with boreal North America [9]. Recent combustion estimates from surface and stand-replacing fires in Eastern Siberian larch forest were on average 3.36 kg C m^{-2} (sd = 0.93 kg C m^{-2}) [16]. The majority of C emissions also stem from belowground pools, albeit to a smaller degree as in North American black spruce forests. The belowground fraction of the total combustion was for example 64.5% in Siberian pine forest and 75% in larch-dominated forest. Fire and timber harvest interact in various ways in southern Siberia, and resulted in higher combustion when woody debris remained on site after logging [17]. Measurements from wildfire combustion in Siberia are complemented by combustion measurements from experimental fires in Scots pine and larch-dominated forests in southern Siberia [18,19]. Combustion from these experimental fires strongly related to the weather conditions during the fire [18].

A rare exception to the combustion measurement shortages in Eurasia is a densely sampled fire in Sweden that occurred in forests dominated by Scots pine [20]. Belowground C combustion was measured in 561 plots and ranged between 0.0 and 15.6 kg C m^{-2}. The lowest combustion occurred in undrained peatlands, and the highest combustion in drained peatlands [20]. The available wildfire combustion measurements in Eurasia give preliminary insights into how C combustion may vary across different fuel types; however, more measurements across fuel types and topographic gradients are required to mechanistically understand drivers of C combustion from wildfires in arctic-boreal ecosystems of Eurasia, including from tundra fires.

Postfire carbon emissions

Postfire C emissions originate from soil respiration, which includes autotrophic root respiration and heterotrophic respiration from decomposition of organic material [21]. Fire removes part of the insulating soil organic layer, which results in thickening of the seasonally thawed active layer in permafrost soils [8]. Fire-induced changes in soil temperature and moisture influence microbial activity and associated CO_2 and CH_4 fluxes. Postfire boreal forest soils typically are a CO_2 source; however, the magnitude of the CO_2 emissions is reduced compared with the emissions from unburned boreal forest soils [7,22,23] and rapidly regrowing vegetation makes most regrowing boreal forests overall C sinks [24]. The reduction in CO_2 emissions can result from reduced availability of labile C after combustion [25], and the prevalence of recalcitrant pyrogenic C in fire-affected soils [26,27]. Ludwig et al.

[25] found that the magnitude of the reduction in postfire soil respiration scaled with fire severity in sparse larch forests, underlain by permafrost, in northeast Siberia. Despite this reduction, postfire soil CO_2 emissions substantially contribute to total fire-induced emissions. Ueyama et al. [23] estimated that the postfire soil emissions amount up to a third of the direct fire C emissions from fire in Alaska, while Potter [22] suggested that the C losses from mineral topsoil after the 2015 fires in Alaska may have been more than double of the direct C combustion losses.

It is important to distinguish between short-cycling C and longer-cycling legacy C when considering postfire soil respiration. This is especially true in permafrost peatlands, which store vast amounts of legacy C. Based on radiocarbon dating, Estop-Aragones et al. [28] found a fivefold higher contribution of legacy C (age = 1600 years before present) in postfire CO_2 emissions in a burned forested peatland in northwestern Canada after deepening of the oxic active layer compared with an intact control peatland. They also compared these fluxes to those from a nearby anoxic thermokarst bog, which had formed after fire, and found no contribution of legacy C to soil respiration of the thermokarst bog [28]. Mineralization of legacy C in peatland soils results from a deeper oxic active layer. This condition may occur after high severity fires, which reduces the peatland's hydrophobic and evaporative cap thereby resulting in higher postfire evapotranspiration [29,30]. This in turn aerates deeper soil C, which then becomes prone to microbial decomposition [31].

The few studies that have examined postfire CH_4 fluxes from boreal soils ranged between no impact of the fire to slight uptake increases [21]. The postfire CH_4 flux of boreal soils is the balance between CH_4 production of methanogenic microbes in anoxic soils and CH_4 consumption by methanotrophs [32]. Little is known about fire-induced changes in CH_4 fluxes from arctic-boreal soils, yet, Davidson et al. [33] and Song et al. [34] showed that topographic position and microtopographic features such as hummocks and hollows had important influences.

Conclusions and research needs

Arctic-boreal fires burn in C-rich peatlands and permafrost soils. They have the potential to release large amounts of terrestrial C to the atmosphere by direct fire emissions and longer-term postfire soil C emissions. Our synthesis of recent literature highlighted that:

- C combustion is dominated by combustion of belowground C, which accounts on average for more than half to 90% of the total combustion among different fuel types.
- C combustion is the highest at intermediate drainage positions, which feature periodically dry and relatively thick organic soils. Intermediate drainage positions are also prone to the combustion of legacy C, especially in young forests.
- Surface fires in Eurasia combust less belowground C than stand-replacing fires in North America, yet recently measured C combustion from stand-replacing fires in larch-dominated forest in eastern Siberia is only slightly lower than combustion in black spruce forests.
- Fire decreases postfire soil CO_2 emissions because of the reduced availability of labile C in soils after combustion and deposition of recalcitrant charcoal.
- Contributions of legacy C to postfire soil CO_2 emissions have been observed in permafrost peatlands.

Several data shortcomings limit our process understanding of C emissions from fire in arctic-boreal ecosystems. Our review revealed the following research needs:

- Assessment of continental variability in C combustion from Eurasian boreal fires across different fuel types and topographic gradients.
- Quantification and understanding of the drivers of C combustion and postfire soil CO_2 emissions in tundra ecosystems.
- Quantification and understanding of the drivers of postfire soil CH_4 emissions after arctic-boreal fires.

Arctic-boreal fires geographically coincide with peatlands and permafrost terrain. Integration of interactive processes between fire severity, topography, vegetation, soils, and permafrost in fire and Earth system models is necessary to accurately estimate the climate feedbacks of arctic-boreal fires.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix. Data and methods

Gridded data

We acquired burned area data from 2001 till 2020 from the 500 m MCD64A1 Collection 6 product [35], which we aggregated to 0.25°. First-order estimates of fire C emissions at 0.25° between 1997 and 2016 were obtained from the Global Fire Emissions Database version

4 with small fires [3]. We discriminated between the boreal forest and arctic tundra biomes based on the biome map from Dinerstein et al. [36]. Peatland coverage was obtained from Hugelius et al. [4] at 10 km resolution as the sum of the histel and histosol coverages, which we spatially averaged to 0.25°. We distinguished between peat-dominated landscapes (peat coverage $>$ 50%), landscapes with peat prevalence (0% $<$ peat coverage $\leq$ 50%) and landscapes without peat. Permafrost zones, including continuous, discontinuous, sporadic, and isolated permafrost zones, were obtained from Obu et al. [37] as vector layers, which we converted to a 0.25° grid based on areal class majority. We obtained fractional tree cover at 250 m spatial resolution for the year 2000 from the MOD44B Collection 6 product [38], which we spatially averaged to 0.25°. We compared arctic-boreal and global burned area and carbon emissions for their overlapping period between 2001 and 2016. We further calculated the distribution of arctic-boreal burned area between 2001 and 2020 relative to continents, biomes, peat coverage classes and permafrost zones.

Field measurements of C combustion

We included field measurements of C combustion from Burenina [15], Delcourt et al. [16], Kukavskaya et al. [14], Mack et al. [13], Walker et al. [6], and Walker et al. [39]. For North America, we discriminated between black spruce-dominated forests and forest dominated by jack pine or deciduous trees based on the proportion of black spruce trees in a site [6]. Black spruce-dominated forest included sites with black spruce density proportions higher than 0.5. Combustion from 20 tundra sites from Mack et al. [13] was complemented with 46 recently measured tundra combustion plots from the Toklat River fire in Alaska [39]. For Eurasia, field plots of Delcourt et al. [16] were dominated by Cajander larch, plots of Kukavskaya et al. [14] by Siberian pine, and the plots of Burenina [15] were located in sparsely forested peatland.

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