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Climate-induced Arctic-Boreal Peatland Fire and Carbon Loss in the 21st Century

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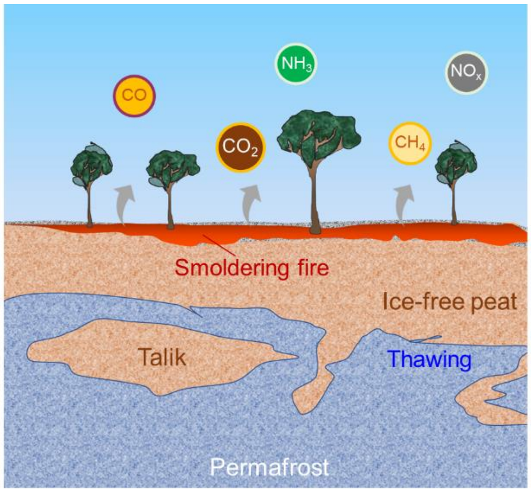
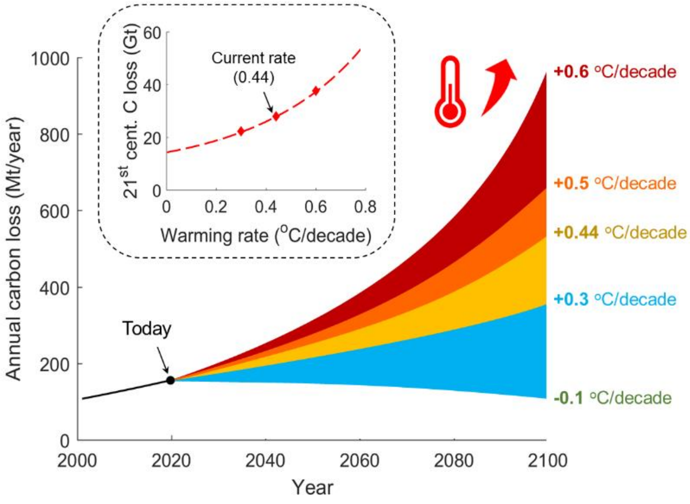
Abstract

Boreal peatlands are increasingly vulnerable to wildfires as climate change continues accelerating. Fires consume substantial quantities of organic soils and rapidly transfer large stocks of terrestrial carbon to atmosphere. Herein, we quantify the minimum environmental temperature from -45°C to 45°C that allows the moist peat to smolder, as the fire threshold of peatlands. We then apply a typical vertical soil temperature profile to estimate the future depth of burn and carbon emissions from boreal peatland fires under the impact of global warming. If the boreal region continues warming at a rate of 0.44 °C/decade, we estimate the carbon loss from the boreal peat fires on a warmer soil layer may increase from 143 Mt in 2015 to 544 Mt in 2100 and reach a total of 28 Gt in the 21st century. If the global human efforts successfully reduce the boreal warming rate to 0.3 °C/decade, the peat fire carbon loss would drop by 21% to 22 Gt in the 21st century. This work helps understand the vulnerability of boreal peatland to more frequent and severer wildfires driven by global warming and estimate climate-induced carbon emissions from boreal peatland fires in the 21st century.

Keywords: *Global warming; Carbon emissions; Peat wildfire; Smoldering fire; Fire ecology.*

Graphical Abstract





1. Introduction

Climate change is accelerating, and its effects are deteriorating as man-made greenhouse gas emissions continue rising (Montzka et al., 2011; Park et al., 2020). In the Arctic and boreal (subarctic) region, the ambient temperature has increased at a warming rate of ~0.44 °C/decade (Batir et al., 2017). As the environmental conditions become more favorable for wildfires, the boreal region has suffered from its worst wildfire season and the longest-lasting burning duration (Helmore, 2019; Héon et al., 2014; Scholten et al., 2021). Unlike the burning of trees and shrubs in lower-latitude regions, a significant portion of boreal wildfires is in the form of flameless burning or smoldering of organic soils and permafrost in peatlands (Vinas, 2019). Peatland wildfire is a climate-sensitive process that may rapidly transfer large stocks of terrestrial carbon to the atmosphere with the annual average of 0.35-1 C Gt/year (Nechita-Banda et al., 2018; Nelson et al., 2021; Page et al., 2002), representing positive feedback that accelerates climate warming as projected by Earth System Models (Krisnawati et al., 2021; Mack et al., 2011).

Peatlands are integral parts of boreal landscapes in the northern hemisphere, occupying roughly 4×10^6 km^2 of Earth land (Zoltai et al., 1998), with around 480 Gt of carbon stored in terrestrial soils (Kohlenberg et al., 2018). Peat consists primarily of partially decayed vegetation accumulated on the Earth surface under acidic, anaerobic, and close to water-saturated conditions (Xu et al., 2018). Pristine peatlands or permafrost in the boreal region can hold a large amount of soil water, and their low temperatures also restrict the direct burning of soils (Grau-Andrés et al., 2018; Lin et al., 2019; Turetsky et al., 2015). However, global warming has already led to changes in the fire regime (Kohlenberg et al., 2018). In the permafrost peatland regions, climate change deepens the active layer (Jones et al., 2015) and makes previously frozen organic matter available to microbial decomposition (Koven et al., 2011), promoting more frequent peatland fires (Gibson et al., 2018; Li et al., 2021).

The upper peat layer is most vulnerable to ambient conditions and often has a high burn severity during wildfires (Wilkinson et al., 2020). During the fire season, the upper soil layer becomes warmer under a higher ambient temperature, so the upper soil layer temperature decreases with depth (Dobinski, 2011). Once ignited from the top surface, the smoldering fire starts to propagate downwards until the deeper soil layer is colder and wetter than the fire threshold. The smoldering fire threshold of peat has been an emerging research topic (Rein and Huang, 2021), and the critical influencing factors include oxygen concentration (Belcher et al., 2010; Huang and Rein, 2016), moisture content (Huang and Rein, 2016), inorganic content (Frandsen, 1987), and fuel configurations (Lin et al., 2021; Lin and Huang, 2021). Although it has been argued that the frequency and severity of wildfires in the arctic-boreal region have been increasing as a result of global warming (Gibson et al., 2018; Veraverbeke et al., 2021), there is still not enough quantitative data on such a trend (Flannigan et al., 2009; Girardin and Mudelsee, 2008; Hanes et al., 2019). Several Earth-system models have been applied to predict the carbon loss from the arctic and boreal regions under global warming (Schuur et al., 2015), but the impact of peatland fires is rarely included. Therefore, it is urgent to understand the fire severity in the arctic and boreal peatlands and the associated fire carbon emissions under different global warming scenarios.

In this work, we interpret the peat fire threshold as a function of the minimum environmental temperature vs soil gravimetric moisture content (MC). A moss peat sample from the boreal forest with high organic content (>97%) was selected, which has the largest heat of combustion and can form a most intense smoldering fire, thus defining the worse peat fire scenario (Lin and Huang, 2020). Afterwards, based on the field measurement of the vertical soil temperature profile in the boreal peatland (Léger et al., 2019), this fire threshold will be used to estimate the depth of burn (DOB) in boreal peatlands. We then further project the carbon emissions from the boreal peatland fires under different global warming scenarios in the 21st century. This research aims to explore how global warming has deteriorated the fire hazards in arctic and boreal peatlands and how this process will give feedback to climate change and impact the Earth ecosystem.

2. Experimental methods

2.1. Peat soil collection

The properties of peat soils may vary with the time, location, and depth, with significant variability and uncertainty. In this work, a moss peat sample from Estonian boreal forest with high organic content (>97%), uniform density and homogenous particle size was selected as the typical boreal peat soil (Fig. 1) (Lin et al., 2020, 2019). Such high-organic content peat soil has the largest heat of combustion and the highest smoldering fire risk, thus defining the worst peat fire scenario. The estimation based on this kind of high-organic peat may provide an upper limit of the depth of burn and the carbon loss.

The peat soil was first oven-dried at 90 °C for 48h, and the oven-dried bulk density was 145 kg/m^3. Afterwards, the oven-dried peat soil was thoroughly mixed with the corresponding water to obtain the desired MC (Lin et al., 2020, 2019). For example, 1 kg of dry peat, by mixing with 1 kg of water, produced 2 kg of wet peat with 100% MC. The mixed peat samples were stored inside a sealed box for natural homogenization for at least another 48 h before the fire tests (Huang and Rein, 2017). As the thoroughly dried peat (i.e., MC $\leq$ 10%) was rare in nature, the targeted MCs for fire tests varied from 25% to 150%, with an interval of 25%.

For each test, the 1.5 L peat sample was placed inside a smoldering reactor that had an inner cross-section area of 10 cm × 10 cm and a height of 15 cm (Fig. 1). The reactor was made of 1-cm thick ceramic insulation boards, and its outer surface was covered by several thin layers of aluminum foil to prevent gas leakage and limit the radiative heat loss (Huang and Rein, 2017). In the process of filling the peat soils into the reactor, the moist sample was consolidated to ensure the dry bulk density fixed to 145 kg/m^3, regardless of the MC.

2.2. Environment control

Experiments were conducted in a temperature-controlled freezer from -45 °C to 20 °C or an oven from 25 °C to 45 °C. The internal volumes of the freezer (40×40×110 cm^3) and oven (44×59×68 cm^3) were two orders of magnitude greater than the 1.5-L smoldering reactor. Two vents with a 2.5-cm diameter were designed on the back of the chamber to ensure that both the oxygen supply and smoke ventilation were sufficient. A small fan was installed inside the chamber to help homogenize the airflow. The oxygen concentration was stabilized at 20.9% (i.e., the atmospheric level) during the burning process, as measured by an oxygen sensor. Several boxes of water/ice were placed inside the chamber, which increased the system thermal inertia and reduced the influence of fire heat release on the controlled environment temperature.

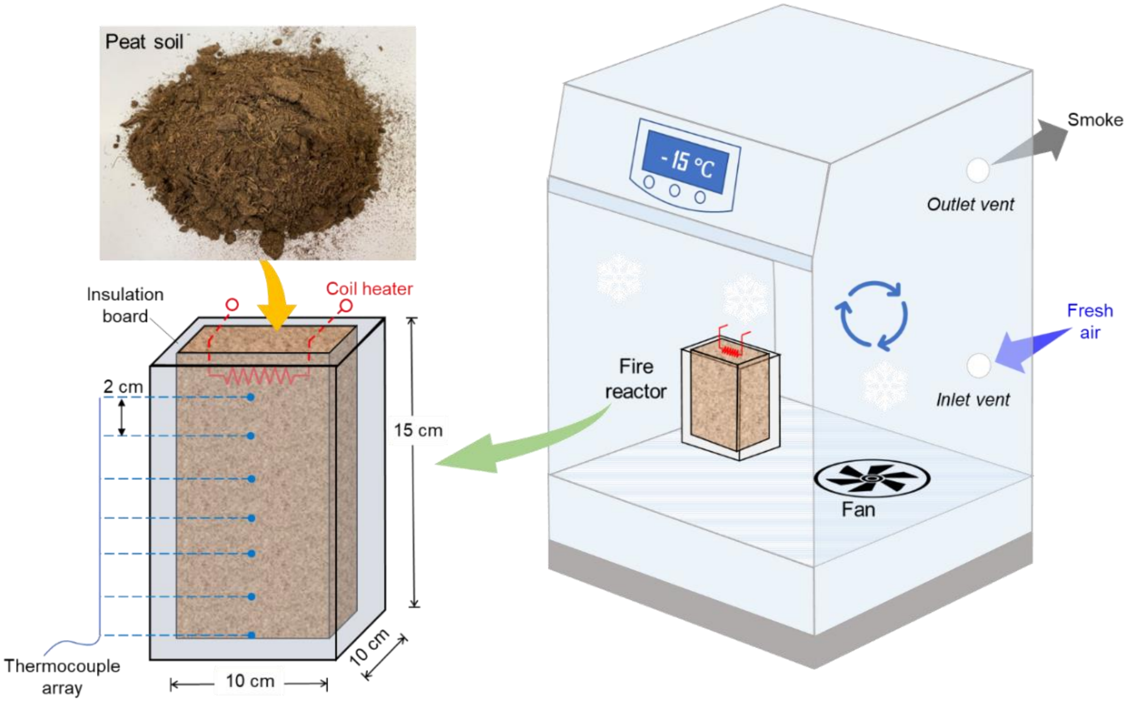


Fig. 1. Photo of peat soil and schematic diagram of the fire reactor and temperature-controlled chamber.

Initially, the temperature inside the chamber was set to a prescribed value and monitored by several thermocouples. To monitor the temperature profile of the peat sample, seven armored K-type thermocouples with a bead diameter of 1 mm were placed from 3 cm to 15 cm below the top free surface with an interval of 2 cm (Fig. 1). When the default temperature sensor of freeze/oven and all thermocouples inside reached the prescribed temperature and stabilized for hours, the desired test environment was ready.

2.3. Initiation of the peat fire

For ignition, a 10-cm long coil heater made of 0.3-mm-diameter $Cr_{20}Ni_{80}$ wire was buried into the peat sample 1.5 cm below the top free surface. The ignition protocol was fixed at 100 W for 30 min, so it was strong enough to initiate a robust and uniform smoldering front in a peat sample with MC up to 150% at the ambient temperature of 20-30 °C (Huang and Rein, 2017; Lin et al., 2020). For the smoldering peat fire, it is difficult to judge the success of ignition and fire spread visually, especially when the fire front is below the free surface (Rein, 2013). Nevertheless, the thermocouple array inside the peat sample could monitor the entire ignition and fire-propagation processes. For a fixed peat MC, if the sample was successfully ignited and self-propagating, the environmental temperature was lowered to test a fresh sample until the fire could no longer propagate. Then, the minimum environmental temperature for this moist peat was found. For each test scenario, at least three repeating fire tests were conducted to quantify experimental uncertainty.

2.4. Estimation of carbon emissions from peat fires

The typical arctic and boreal peat layer temperature profile during the fire season in Alaska was applied to estimate the depth of burn (DOB), where the soil temperature decreases with depth (Léger et al., 2019). From a database of 12,705 measurements, the average MC of northern hemisphere peat within the upper peat layers down to 58 cm is about 82% (Smith et al., 2012). Note that there is a large uncertainty in the field measurement of DOB, which is affected by the peat properties, moisture and environmental conditions (Kohlenberg et al., 2018; Lukenbach et al., 2015). It was assumed that the ignited smoldering fire would propagate downward until reaching the soil layer where the temperature was too cold to maintain the fire. This minimum environmental temperature is defined as the peatland fire threshold. Then, we can estimate the possible depth of burn if the fire occurs.

Afterwards, the carbon emission flux of the burnt peatland ($\dot{m}_C''$) [kg C/m^2] is estimated as $\dot{m}_C'' = \rho \cdot C \cdot DOB$, where ρ is the dry bulk density of soil on the surface layer of boreal peatland, and C is the carbon mass fraction of peat (Mack et al., 2011; Page et al., 2002). It was also assumed that the peatland soil temperature profile near the ground surface would increase simultaneously at the same rate as atmospheric temperature (Batir et al., 2017). The annual carbon emissions from all peatland fires [Mt/year] is estimated as $\dot{m}_C = \eta \cdot A \cdot \dot{m}''_C$, where η and A are the annual burn probability [%/year] and the total land area [km^2] of peatlands, respectively.

3. Results and Discussion

3.1. Peat fire behaviors

Our experiments reveal the fire threshold of peatlands on Earth, that is, the minimum environmental temperature that just allows a self-sustained smoldering fire on the peat soil. Fig. 2 shows the temperature measurements of two experimental cases at the controlled environmental temperature of -5 °C, where one sample has the MC of 25% (Fig. 2a), and the other has the MC of 75% (Fig. 2b). Before ignition, the peat sample was cooled down to the prescribed environment temperature and stabilized for several hours. During the ignition process, the temperature near the electrical heater quickly increased above 400 °C, indicating a robust heating process. After 30 min, the heating power was turned off, then a sudden drop in temperature was observed. A successful ignition was defined if the smoldering fire propagated downwards with the soil temperature above 250 °C for a significant period after the external heating (Fig. 2a) (Belcher et al., 2010; Lin and Huang, 2021). In contrast, a failed ignition was defined if all measured soil temperatures decreased gradually to the environmental temperature after the heating source was turned off (Fig. 2b).

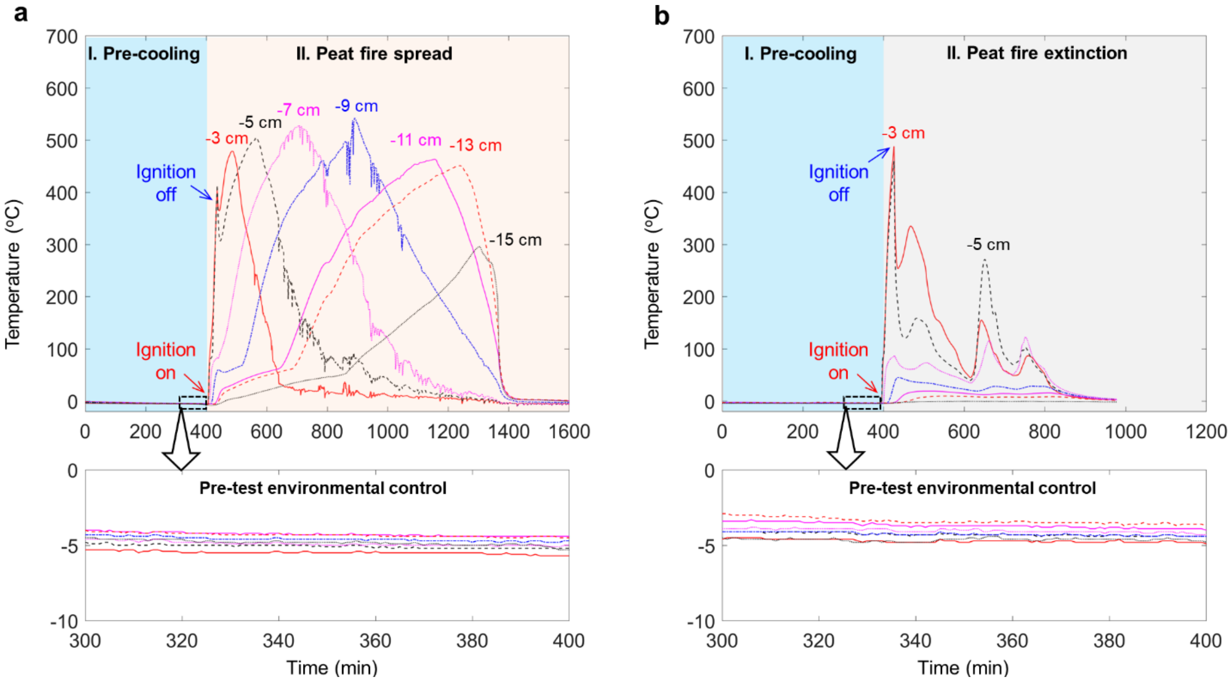


Fig. 2. Thermocouple data of (a) successful smoldering propagation in the peat of MC=25%, and (b) failed smoldering spread (extinction) in the peat of MC=75% at the environmental temperature of -5 °C.

3.2. The vulnerability of boreal peatland

Fig. 3 summarizes the fire threshold of peat on Earth in terms of the minimum environmental temperature that just allows a self-sustained smoldering fire (T_{crt}). As expected, the minimum temperature that allows the smoldering of peat soil increases with the soil moisture. For example, as the MC increases from 50% to 75%, the minimum temperature increases from -20 °C to 5 °C. For the relatively dry peat (25% MC), the fire can survive at -35°C through the cold artic winter, and for the very dry peat (10% MC), it can even smolder below -45°C. This is the fundamental reason why the over-wintering peat fire can survive in the arctic-borean region (Scholten et al., 2021).

For the frozen soils or permafrost (< 0 °C), if the MC is higher than 75%, it is resistant to a smoldering fire. However, global warming drives the soil temperature to continue increasing at the rate of about 0.44 °C/decade in boreal peatlands (Batir et al., 2017); thus, the vulnerability of peatland to smoldering wildfires may increase over time. With the severity indicated by massive burnt soils, the deteriorating peatland fire can release a tremendous amount of terrestrial carbon to accelerate global warming, creating positive feedback.

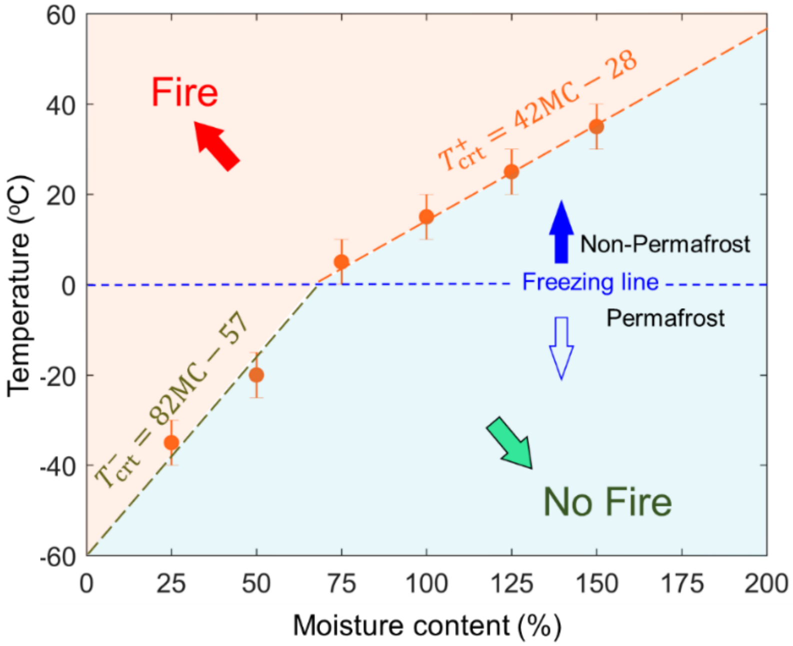


Fig. 3. The vulnerability of peat soil with different gravimetric moisture contents, represented by the minimum environmental temperature that allows a self-sustained smoldering front to propagate, where the error bars show the standard deviations.

Two linear correlations were found for the smoldering fire threshold of peatland as a function of the minimum environmental temperature (T_{crt}) and the peat gravimetric moisture content (MC), that is, $T_{crt}^{-} = 82\text{MC} - 57$ for the frozen peat soil (or permafrost) and $T_{crt}^{+} = 42\text{MC} - 28$ for nonfrozen peat soil. As extra heat is required to thaw the permafrost, the fire threshold of frozen peatlands (permafrost) is more sensitive to the soil moisture profile (see analysis in *Supplementary Information*). The average MC of 82% for the boreal peatland, based on massive field measurements (Smith et al., 2012), was used in the subsequent analysis. With this MC, the corresponding minimum environmental temperature allowing a stable smoldering peat fire is about 6.5 °C. Although global warming may dry the soil and reduce the soil moisture, such an effect may be compensated by the increase in precipitation (Wang et al., 2017). Thus, compared to the soil temperature, the average MC in boreal peatlands may be less sensitive to global warming.

3.3. Depth of burn and carbon loss

If a smoldering fire is ignited on the peatland by lightning or human activities, it will spread both laterally and in-depth until the soil layer is too cold or too wet to maintain the fire. After extinction, the depth of burn (DOB) can be used to estimate the fire emissions (Page et al., 2002). Fig. 4(a) shows the vertical summer soil temperature over the top 1.5 m based on the measurement of a long-term monitoring station in the boreal peatland of Alaska (Léger et al., 2019). During the hot and dry fire season, the soil temperature shows a decreasing trend with the depth over the top layer (Dobinski, 2011).

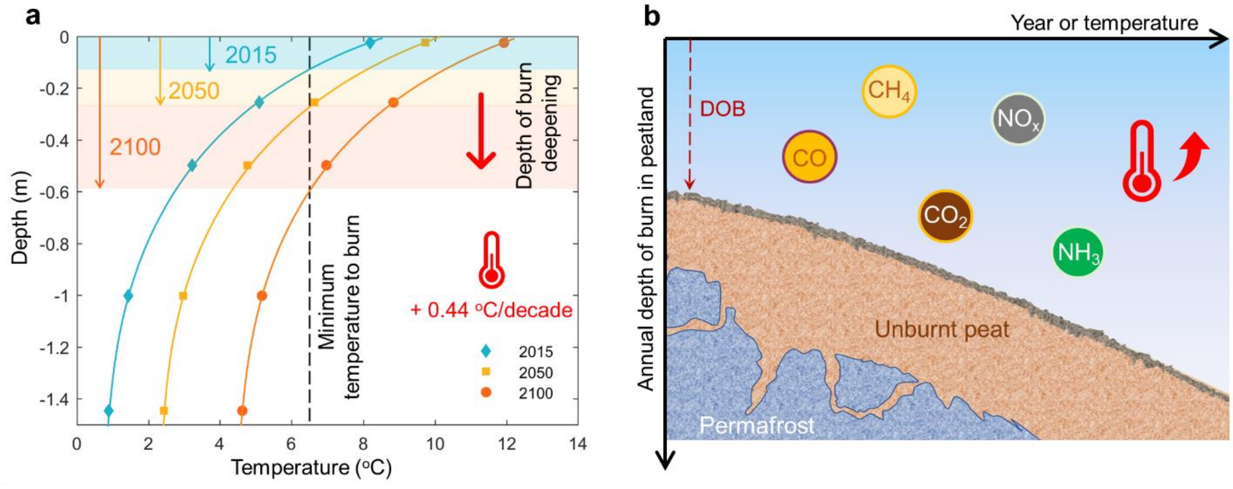


Fig. 4. (a) The measured vertical soil temperature profile in Alaska in the summer of 2015 (Léger et al., 2019) and the projected temperature profile in 2050 and 2100 at the warming of 0.44 °C/decade (Batir et al., 2017), where the shadow part represents the potential deepening depth of burn per smoldering peatland fire due to the global warming, and (b) simplified illustration of the trend of the depth of burn (DOB) with the increasing atmospheric temperature with time.

Under the current global warming rate, the temperature of boreal peatland is estimated to increase at the rate of 0.44 °C/decade (Batir et al., 2017), and Fig. 4(a) also shows the expected soil temperature profile in 2050 and 2100. We then illustrate the fire threshold of peat (i.e., 6.5 °C) from Fig. 3 in terms of average soil moisture of 82% (plotted as black dash line), and the potential DOB could be quantified if a fire occurs (Fig. S2b). Note that the local soil moisture may vary with depth, so the rough estimation here is an average value in the global scale. Fig. 4(b) further illustrates the influence of increasing atmospheric temperature with time on the depth of burn (DOB).

Fig. 4 also shows that based on the acquired fire-threshold boundary, the top 0.16 m thick boreal peat layer would be burnt during wildfires in 2015. This predicted DOB is close to multiple field measurements at several boreal and subarctic peatlands in Russia (Sirin et al., 2020), Alberta, Canada (Benscoter et al., 2011), Scottish Highlands (Davies et al., 2013), and Northern Alaska (Mack et al., 2011), whereas it is lower than that in tropical peatland fires (Ballhorn et al., 2009; Page et al., 2002). Thus, the reliability of this model is verified by the historical data. Under the warming rate of 0.44 °C/decade, the potential depth of burn is projected to increase to about 0.28 m in 2050 and 0.60 m in 2100, showing 79% and 280% increments from year 2015 (Fig. S2b).

Based on our model, an empirical correlation can be established to estimate future DOB [m] in boreal peatlands as a function of the soil moisture (MC), global warming rate (α) [°C/decade], and year (Y) as

$$DOB = 2.36[42\mathrm{MC} - 28 - 0.1\alpha(Y - 2015)]^{-0.38} - 1 \quad [\mathrm{m}] \tag{1}$$

The R^2 coefficient of this correlation is 0.92. If the soil is severely dried to MC < 70%, the fire has the potential to reach the frozen soil layer (permafrost) with a greater depth of burning, following $DOB = 2.36[82MC - 57 - 0.1\alpha(Y - 2015)]^{-0.38} - 1$. Although such peatland fire scenarios are still rare under the current arctic and boreal temperature, such a probability may increase in the future driven by the accelerating climate change.

Referring to literature measurement (Belcher et al., 2010; Huang and Rein, 2019; Lin et al., 2019; Mack et al., 2011; Treat et al., 2016), the mean carbon content of boreal peat is relatively stable at around 45±5%, while the dry bulk density has a wide range from 50 to 300 kg/m^3 and increases with the depth. By using a typical dry bulk density of 100 kg/m^3, the current carbon emission flux from smoldering peat fire is estimated to be 7.1 kg C/m^2 (Fig. S2c), which is within the field measurement of 0.4-9.5 kg C/m^2 during the 2007 Anaktuvuk River fire in Alaska (Mack et al., 2011; Oechel et al., 2000).

About 0.5% of the entire boreal peatland is expected to burn annually (Zoltai et al., 1998). Thus, the average carbon loss flux from the entire boreal peatland is 0.036 kg C/m^2/year in 2015, which is higher than the annual net ecosystem carbon gain without fire (0.03 kg C/m^2) (Mack et al., 2011; Oechel et al., 2000; Shaver and Chapin, 1991). Peatlands are the most abundant in the boreal region, where they cover roughly 4×10^6 km^2 of Earth land, that is, 80% of peatland in the world (Turetsky et al., 2015). Under the burn probability of 0.5% (Zoltai et al., 1998), the annual total burned area is estimated to be 2×10^4 km^2/year in the boreal peatland. We can then estimate that the annual carbon loss from arctic-boreal peat wildfire in 2015 is around 143 Mt C/year (Fig. 5), which contributes to 15–40% of the average carbon loss from global peat fires emission (0.35–1 Gt C/year) or 1.4% of current global manmade carbon emission (~10 Gt/year) (Nechita-Banda et al., 2018; Nelson et al., 2021; Page et al., 2002). This value is also about 50 times the annual net C sink for the entire arctic and subarctic tundra biome (3-4 Mt C/year) (Mcguire et al., 2009).

3.4. Carbon loss at different global warming scenarios

As the DOB is expected to increase with global warming, we can scale up Eq. 1 and predict the future carbon emission flux per peat fire [kg C/m^2] after the year 2015 as $\dot{m}''_C = 106[42 \cdot \mathrm{MC} - 28 - 0.1\alpha(Y - 2015)]^{-0.38} - 45$. Under the current boreal warming rate of 0.44 °C/decade (Batir et al., 2017), the carbon emission flux may increase from 7.1 kg C/m^2 in 2015 to 12.8 kg C/m^2 in 2050 and 27.2 kg C/m^2 in 2100 (Fig. S2c). Then, by assuming that the annual burn probability is fixed to 0.5%/year in the 21st century, we can predict the future annual carbon emissions from all boreal peatland fires [Mt C/year] as

$$\dot{m}_C = 2100[42MC - 28 - 0.1\alpha(Y - 2015)]^{-0.38} - 900 \qquad [\mathrm{Mt\ C/year}] \qquad (2)$$

Thus, the warmer peatland is estimated to release approximately 256 Mt C/year in 2050 and 544 Mt C/year in 2100, that is, almost 100-200 times of annual net C sink for the current entire arctic tundra biome (Mcguire et al., 2009).

Given a global warming rate (α) [°C/decade], we can further estimate the net cumulative carbon loss over the entire 21st century as $\dot{M}_C = 13.2e^{1.7\alpha}$, where $R^2 = 0.99$. Under the current boreal warming rate of 0.44 °C/decade, the net cumulative carbon loss over the entire 21st century is projected to be 28 Gt (see subplot in Fig. 5 and Fig. S2d). Such a carbon loss is almost three times that from burning fossil fuels in 2014 (~10 Gt) (Boden et al., 2017) and 1.6% of 1,700 Gt carbon stock in permafrost (Reyes and Cooke, 2011; Schuur et al., 2015; Turetsky et al., 2019).

The anthropogenic greenhouse gas emissions are expected to increase in the next few decades continuously (Mcguire et al., 2009). The Intergovernmental Panel on Climate Change (IPCC) estimates that the Earth will warm by 6 °C in the 21st century, if the whole world has not implemented any climate reduction policies (IPCC, 2007). Therefore, herein we further estimate the potential carbon loss during the fires at different warming scenarios by the year 2100 (Fig. 5). If future human-made greenhouse emissions further exacerbate the boreal warming rate to 0.6 °C/decade, the potential carbon loss from all boreal peatland fires may increase to 969 Mt in 2100, which is almost seven times the current level and doubles the emissions in 2100 under the current warming rate of 0.44 °C/decade. Consequently, the total carbon loss may reach 38 Gt during the 21st century.

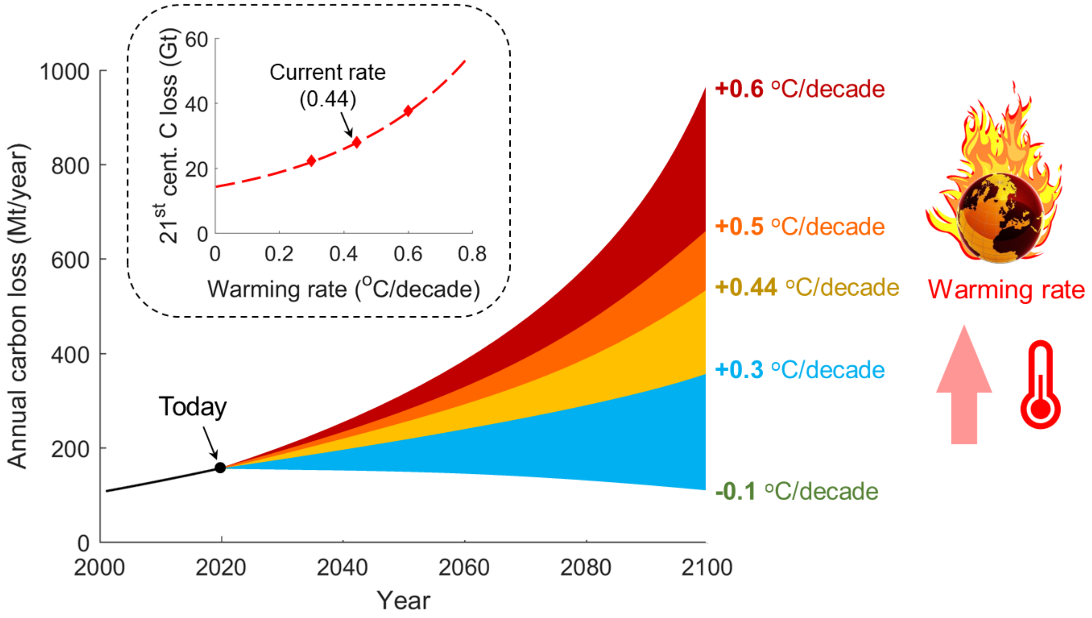


Fig. 5. Estimates of annual carbon loss in the 21st century from boreal peatland fires under different warming scenarios.

On the other hand, if current climate and energy policies are successfully implemented to reduce the warming rate to 0.3 °C/decade, we estimate a reduced carbon loss to 360 Mt in 2100, that is, about 21% decrease compared to the current warming rate, and the total carbon loss may decrease to 22 Gt during the 21st century. Therefore, slowing down the global warming rate may effectively reduce greenhouse gas emissions from peatland fires.

3.5. Fire impact on the Earth ecosystem

Nitrogen is one of the critical elements that control plant productivity in the ecosystem. Therefore, the soil nitrogen loss in fires will affect the postfire carbon absorption for an extended period (Mack et al., 2011; Szép et al., 2019). Herein, we simultaneously estimate the nitrogen (N) loss from boreal peatland fires (Fig. S3). Assuming the mean peat nitrogen content of 1.5% (Treat et al., 2016) and the same burn probability of 0.5% (Zoltai et al., 1998), the estimated average nitrogen loss flux from the entire boreal peatland is 1.19 g N/m^2/year in 2015, and it is expected to sharply increase to 4.54 g N/m^2/year in 2100 under the current trend of warming. In contrast, the annual nitrogen accumulation rate due to both deposition and biological fixation in Alaska is estimated to be at most 0.16 g N/m^2/year (Hobara et al., 2006; Mack et al., 2011), which is one order of magnitude smaller than the nitrogen loss rate. Therefore, the nitrogen loss from smoldering fire in peatlands is an irreversible process and even worse than carbon loss.

Except for the direct carbon emissions through extensive burning, in the permafrost regions, the wildfires in peatlands also have a long-term impact on the deeper permafrost layer. For example, it was estimated that the postfire ground thermal conductivity might increase ten times, whereas the surface albedo may decrease by 50% (Yoshikawa et al., 2003). Furthermore, wildfires in peatlands within permafrost regions cause the unburned permafrost to thaw through the deepening of the active layer and the expansion of talik on the peat plateaus (Fig. 4b) (Gibson et al., 2018). The impacts of permafrost thawing include increasing surface runoff, dissolving organic matter and methylmercury in surface water, loss of wildlife habitat, reducing land use, and increasing greenhouse gas emissions due to the microbial decomposition (Ding et al., 2019; Gibson et al., 2018; Schuur et al., 2015). It was projected that no peatland permafrost would remain after global warming for 6 °C (Hugelius et al., 2020), and more frequent wildfires would accelerate this process (Gibson et al., 2018).

Projections also suggest that the slow thawing could release about 200 Gt of carbon over the next 300 years under the current warming scenario (Turetsky et al., 2019). Nevertheless, it might be vastly underestimated without considering the carbon emissions from peatland fires. As we projected, the carbon emissions from boreal peatland fires may accelerate under climate warming. Because of the extensive in-depth heating and the removal of the top soil layer by the underground peat fires, the extent of permafrost thaw may also expand. With the postfire expansion of thawing permafrost, substantial quantities of organic soil may become vulnerable to biodegradation by microorganisms (Gibson et al., 2018). Consequently, enormous greenhouse gases, including carbon dioxide, methane, and nitrous oxide, can be released into the atmosphere, intensifying the positive feedback to climate change and deteriorating the ecosystem (Biskaborn et al., 2019; Camill, 2005; Turetsky et al., 2019).

The extensive wildfires could transport substantial quantities of particulates and volatile compounds via the atmosphere and produce large fluxes of nutrients into the ocean ecosystem (Shirokova et al., 2021; Spencer et al., 2003). In particular, the cycle of nitrogen and phosphorous are two main contributors to the ocean's primary productivity (Kump and Mackenzie, 1996). Fire improves the supply of nitrogen (N) and phosphorous (P) to the ocean either via aerial deposition from aerosol and smoke or by increasing the influx of ash (rich in phosphorous) into the ocean (Belcher et al., 2010). The increase of phosphorous and nitrogen contributes to the growth and reproduction of aquatic plants, algae, and cyanobacteria (Smith et al., 2011; Spencer et al., 2003). The resulted oxygen reduction in the water may cause massive deaths of fish and other species and release enormous toxic gases (Santos et al., 2015). As we predict a climate-induced increase of fire severity and precipitation in boreal peatlands, these extra nitrogen and phosphorous fluxes from fires would potentially exacerbate global water eutrophication and ecological damage. Therefore, it is imperative for water quality management strategies to consider the impact of increasing peatland fires on marine ecosystems.

4. Conclusions

In this work, we reveal the smoldering fire threshold of boreal peatlands as a function of environmental temperatures (-45 - 40 °C) and gravimetric moisture contents (25% to 150%). Based on the data of vertical soil temperature profile, we then successfully predict the depth of burn in boreal peatlands to be 0.16 m in 2015 that is close to multiple field measurements. We predict the future depth of burn as $DOB = 2.36[42\mathrm{MC} - 28 - 0.1\alpha(Y - 2015)]^{-0.38} - 1$, given a boreal warming rate, α (°C/decade). Under the current boreal warming rate of 0.44 °C/decade, we estimate that the carbon emissions per unit burnt boreal peatlands may increase from 7.1 kg C/m^2 in 2015 to 12.8 kg C/m^2 in 2050 and 27.2 kg C/m^2 in 2100. With a burning area of 0.5%, the total soil carbon emissions in the entire 2×10^4 km^2 boreal peatlands may increase from 143 Mt in 2015 to 256 Mt in 2050 and 544 Mt in 2100. The cumulative carbon loss of the 21st century is estimated to be 28 Gt, which is three times of emissions from burning fossil fuels in 2014.

If the current energy policies successfully reduce the warming rate to 0.3 °C/decade, we predict a reduction of one third carbon emissions from boreal peatland fires. With increasing fire frequency and severity under a warming climate, emissions from boreal peatland fires are expected to influence the ecosystem through multiple biogeochemical processes. This research helps evaluate the fire risks of boreal peatlands and estimate climate-induced carbon emissions from boreal peatland fires in the 21st century. Future research will focus on quantifying the influence of different parameters on our model and further improving the predictions of peat fire carbon loss.

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CRediT author statement

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Competing interests.

The authors declare no conflicts of interest.

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