Impact of Snow on Underground Smouldering Wildfire in Arctic-Boreal Peatlands

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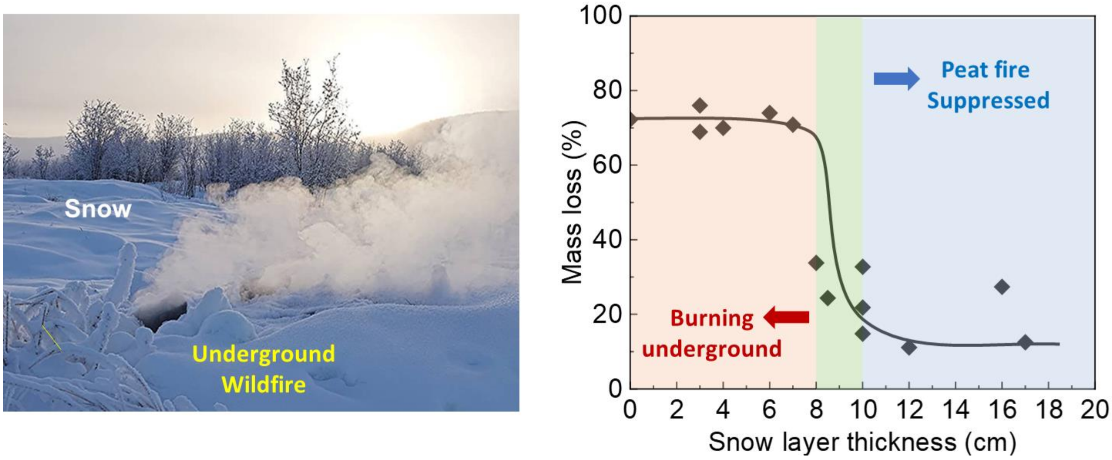
Abstract

Overwintering peat fires are re-emerging in snow-covered Arctic-boreal regions, releasing record-breaking carbon into the atmosphere which exacerbates climate change. Interactions between fire and snow are an important natural process, but our understanding of it is still limited. Herein, small-scale experiments (20 × 20 × 20 cm^3) were conducted outdoors at cold ambient (< 0 ^{o}C) to understand the effect of natural snowfall and accumulated snow layers (up to 20 cm thick) on the development of shallow smouldering peat fires. We found that, even heavy natural snowfalls (a maximum water-equivalent snowfall intensity *of* 1.1 mm/h or a 24-h accumulated snowfall precipitation *of* 7.9 mm) cannot suppress a shallow smouldering peat fire. A thick snow cover on the peat surface can extract heat from the burning front underneath, and the minimum thickness of the snow layer to successfully extinguish the peat fire was found to be around 9 ± 1 cm, agreeing well with the theoretical analysis. The required precipitation for suppressing peat fire in Arctic-boreal regions was predicted to be lower than that in tropical regions due to the lower ambient temperature and additional heat of melting snow. Finally, larger-scale field demonstrations (1.5 m × 1.5 m) were conducted to further reproduce and validate the fire phenomena of small-scale experiments. This work helps understand the interactions between fire and snow and reveals the persistence of smouldering wildfires under cold environments.

Keywords: *wildland fire; zombie fire; outdoor experiment; peat fire suppression; snow precipitation.*

Graphical Abstract



1. Introduction

Peatlands are important ecosystems that have accumulated partially decomposed vegetation residues under acidic, water-saturated and anaerobic conditions (Hugron et al., 2013). Although peatlands only cover ~ 3% (4 ×10^6 km^2) of Earth's land surface, they are important terrestrial carbon sinks storing over one-third of the global soil organic carbon (500–600 Gt C), approximately equal to those stored in living plants and atmosphere (Immirzi et al., 1992; Kleinen et al., 2012; Page et al., 2011; Xu et al., 2018; Yu et al., 2010). The global peatlands are mainly distributed in tropical (primarily Southeast Asia) and Arctic-boreal regions (the northern high latitudes of the Americas, Europe, and Asia) (Anshari et al., 2022; Rydin et al., 2013a; Xu et al., 2018), playing an important role in promoting carbon cycling, regulating hydrological processes, and nurturing biodiversity (Eville Gorham, 1991; Rydin et al., 2013b).

However, global peatlands are becoming more vulnerable to severe and frequent wildfires due to the accelerating climate change (Rein et al., 2009, 2008; Słowiński et al., 2022; Walker et al., 2019; Witze, 2020). Over the past few decades, the increasing prevalence of deep underground peat fires has led to the widespread destruction of peatland ecosystems and substantial emissions of greenhouse gases (GHG) (Gao et al., 2023; Hu et al., 2018; Kohlenberg et al., 2018; Sazawa et al., 2018; Volkova et al., 2021). These GHG emissions, in turn, might give positive feedback to climate change, posing a severe threat to peatland ecosystems by increasing wildfire risk (Flannigan et al., 2009; Galizia et al., 2023; Rein and Huang, 2021; Senande-Rivera et al., 2022), carbon loss (Chen et al., 2020; Descals et al., 2022; Krisnawati et al., 2021; Lin et al., 2021b), permafrost thawing (Chen et al., 2021; Gibson et al., 2018; Hugelius et al., 2020; Jorgenson and Jorgenson, 2021; Manasypov et al., 2017; Schuur et al., 2015), and atmospheric pollution (e.g., CO, NO_x, $PM_{2.5}$, etc.) (Chakrabarty et al., 2016; Hinwood and Rodriguez, 2005; Hu et al., 2018; Liu et al., 2023; Mccarty et al., 2021). Furthermore, compared to the vegetation consumed by the surface fires, peatlands are not able to recover rapidly following a deep-propagated fire event, resulting in the irreversible release of carbon into the atmosphere (Mack et al., 2011; Witze, 2020). In Arctic-boreal regions, even though the cold ambient and (frozen) soil water may restrict the severity of fires, recent measurements indicate that wildfires are erupting at a record-breaking pace (Witze, 2020). Many overwintering fires have been observed in Alaska, U.S.A. and the Northwest Territories, Canada, which may account for ~ 3.5 Tg of carbon emissions in the last two decades (Scholten et al., 2021).

Smouldering is the dominant burning phenomenon of wildfires in peatlands (Rein and Huang, 2021). It is a persistent type of combustion that is characterised as a slow, low-temperature, and flameless process in porous charring fuels (Lin et al., 2021a; Ohlemiller, 1985; Rein, 2014, 2013). Smouldering wildfires occur more readily than flaming fires and survive under lower temperatures, higher moisture contents, and lower oxygen concentrations (Huang and Rein, 2016a, 2015; Lin et al., 2019; Qin et al., 2022a; Turetsky et al., 2015). For example, our previous laboratory experiments have demonstrated that smouldering peat fires can survive below -40 ^{o}C (Lin et al., 2021b) and persistently burn 1 m below the ground for weeks (Qin et al., 2022b). Furthermore, smouldering hot spots can hide and creepingly spread underground for months and even years, awaiting the advent of dry and warm seasons to flare up, known as "zombie fires" (McCarty et al., 2020; Qin et al., 2022b; Scholten et al., 2021; Zhang et al., 2024). Limited studies have been also conducted to explore the environmental influences from the perspectives of topography change (Lin et al., 2021c), hydrological regime (Schulte et al., 2019), precipitation suppression (Lin et al., 2020; Santoso et al., 2021), diurnal variation (Santoso et al., 2022), etc. Nevertheless, the complicated smouldering behaviours under real scenarios are still poorly understood, requiring more fundamental research.

Snow is a crucial part in Arctic-boreal ecosystems that covers these regions for up to 9 months in a year (Boelman et al., 2019), which plays important roles in land-surface energy balance (Swenson and Lawrence, 2012). However, spring snow cover was found to decrease 7~11% per decade over the Northern Hemisphere since the 1970s, due to the accelerating climate change (Brown and Robinson, 2011). The reduction in snow cover will expose darker surfaces like soil or vegetation with lower albedo, weakening the role of reflecting solar radiation back into space (Groisman et al., 1994). As a result, the lower reflectivity of these surfaces absorbs more solar radiation, creating a positive feedback loop to amplify the effects of climate change. Moreover, apart from snowmelt caused by climate change, wildfires are another driver of the snow melting, which further accelerates and exacerbates the effect of climate change (Brown et al., 2015; Dymov et al., 2022; Gibson et al., 2018).

Recently, more peat fires occurring in snow-covered areas have been observed (see the example in the *Graphical Abstract*, where peat fires burnt under snow cover at -60 °C in *"the Pole of cold"*, Russia (Credit: Semyon Sivtsev)) and detected by remote sensing technology (Scholten et al., 2021). Although peat fires are recognized as a key contributor to the snow melting and permafrost thawing, whether the snowfall and snow cover will in turn affect the burning dynamics of smouldering wildfires is still unclear. Therefore, the objectives of this study are: (1) to investigate the impact of natural snowfall on peat fires, specifically if a natural snowfall can suppress a peat fire; (2) to examine the role of snow cover on peat fires, considering whether it acts as a surface insulation layer or an extinguishing agent; (3) to quantify the potential influence of melted snow on the behaviours of peat fires. To fill these knowledge gaps, it is necessary to thoroughly investigate the interactions between snow and peat fires.

This work conducted a group of small-scale outdoor experiments (20 × 20 × 20 cm^3) in the winter at the boreal region of Inner Mongolia, China. Underground peat fire tests below the freezing line (0 °C) revealed the effect of (I) natural snowfall (SF) and (II) accumulated snow layers (SL) with a thickness of up to 20 cm on the development of shallow smouldering peat fires. Furthermore, a physics-based theory was proposed to explain the experimental data and further predict the criteria for suppressing smouldering underground fire via precipitation in the Arctic-boreal regions. Finally, large demonstrations (1.5 m × 1.5 m) were performed with both natural snowfall and snow cover to validate the small-scale observations.

2. Materials and methods

2.1. Peat soil samples

Moss peat soils from Estonia were selected for the experiments. This peat with uniform density, elemental composition and particle size can ensure better experimental reproducibility, as demonstrated in our previous studies (Lin et al., 2021c, 2020; Lin and Huang, 2021; Qin et al., 2022b). The peat soil had a porous structure (porosity ≈ 0.9), a high organic content (> 95%), and a dry bulk density (ρ_p) of 145 ± 15 kg/m^3.

In real peatlands, the moisture contents (MC) of peat soil varied and were influenced by seasonal and climate factors, the position of the water table, and its associated hydrological responses

(Waddington et al., 2015). To focus on the role of snow and minimise the effect of fuel moisture content on experimental results, all the peat samples were pre-dried in an oven at a constant temperature of 75 °C for at least 48 h. Afterwards, the pre-dried samples were preserved in sealed boxes to prevent samples from absorbing ambient moisture. Before tests, subsamples showed that the MC was close to 5%, which had a negligible effect on the smouldering fire behaviours (Hu et al., 2019; Huang and Rein, 2016a; Lin et al., 2021b).

2.2. Peat fire tests

All experiments were performed outdoors in Inner Mongolia, China (Fig. 1a). The local diurnal temperature variation was lower than 20 °C with an average temperature below the freezing point (i.e., 0 °C, exemplified in Fig. 2). Such low environmental temperatures were used for simulating the fire environments in the Arctic-boreal regions. Pits with a dimension of 20 × 20 × 20 cm^3 were made in the frozen soil layer to conduct fire experiments. These frozen soils had a higher water content (> 100%) and a lower organic content (< 20%), thus the burning areas could be well isolated to protect the surrounding lands from uncontrolled wildfires. At the same time, they enabled the heat loss and oxygen supply in the lateral direction, making the test condition closer to the real fire scenarios than those small-scale laboratory experiments.

For each experiment, the peat sample was placed into the pit at least 2 h before the test to achieve thermal equilibrium with the surrounding environment. Afterwards, a propane flame was used to ignite the peat column from the top surface for around 2 min. An array of five K-type thermocouples with a bead diameter of 1 mm was inserted into the axis of the peat at different depths (from 0 cm (surface) to -20 cm (bottom) at an interval of 5 cm) to measure the vertical temperature profile at a time interval of 1 min. Another thermocouple was placed near the ground to record the ambient temperature. For each fire scenario, at least three repeating tests were conducted to ensure test reproducibility.

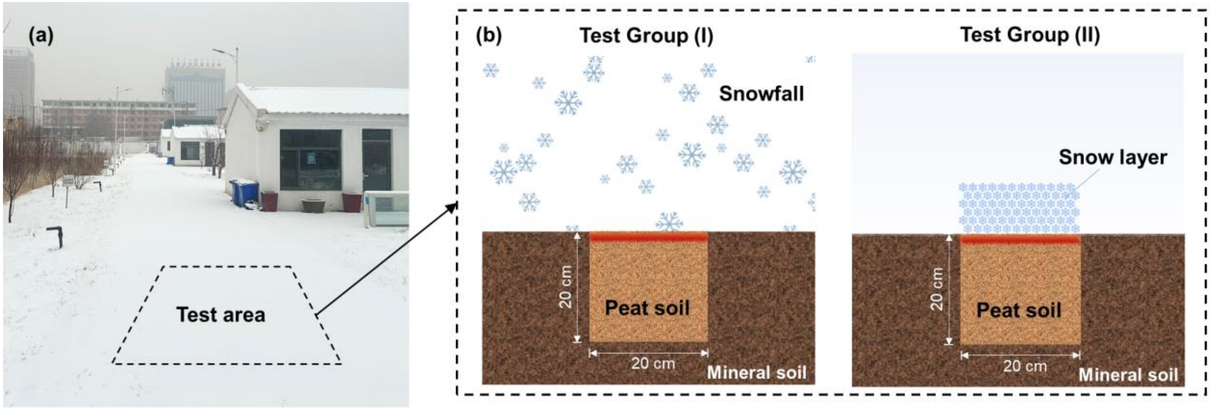


Fig. 1. (a) Photo of the test area in this work in Inner Mongolia, China, and (b) diagram of small-scale experimental design: the effect of (I) natural snowfall and (II) accumulated snow layer on peat fires.

Table 1. The classification of snowfall intensity, by using the Liquid Water Equivalent Systems (LWES), compared with rainfall in brackets (AMS, 2013a; CMA, 2018a; WMO, 2018a).

Classification	Snowfall (Rainfall) intensity [mm/h]	Snowfall (Rainfall) in 24 h [mm]
Light	< 1 (< 2.5)	<2.5 (< 10)
Moderate	1 - 2.5 (2.5 - 10)	2.5 - 5 (10 - 25)
Heavy	2.5 - 10 (10 - 50)	5 - 10 (25 - 50)
Violent	> 10 (> 50)	> 10 (> 50)

2.3. Design of snow impact

There are two types of snow impact, one is the dynamic snowfall, and the other is the snow layer accumulated from the previous snowfall. The average bulk density of the snow layer (ρ_{SL}) was measured to be 265 ± 20 kg/m^3. Similar to the classification of rainfall intensity, the intensity of snowfall also has two classification standards, namely, the maximum snowfall intensity and the cumulative precipitation in 24 hours. Measured by the ground meteorological station, they are divided into Light (< 1 mm/h or 2.5 mm), Moderate (1 - 2.5 mm/h or 2.5 - 5 mm), Heavy (2.5 - 10 mm/h or 5 - 10 mm) and Violent (> 10 mm/h or > 10 mm), depending on its intensity and accumulation of its equivalent liquid water during a certain period (AMS, 2013b; CMA, 2018b; WMO, 2018b) , as shown and compared in Table. 1. The average environmental temperature during the whole experimental period was around -5 ºC, and the minimum temperature was as low as -18.2 ºC, as summarized in Table 2. Two groups of experiments were designed, as illustrated in Fig. 1b, to investigate the snow impact on Arctic-boreal peat fires:

(I) Effect of natural snowfall (SF tests) on smouldering peat fires. Fire tests, including the ignition and fire propagation processes, were conducted with outdoor ongoing natural snowfall. Both snowfall intensity (water equivalent value, mm/h) and 24-hour accumulated precipitation (see Table 1) were confirmed by the China National Meteorological Science Data Centre (https://data.cma.cn/dataService). To ensure the repeatability of the experiment and maximize the use of each snowfall, three independent experiments were conducted at the same time under each natural snowfall scenario. The total mass loss before and after the fire was also measured to indicate the influence of snow on peat burning.

Table 2. Summary of experimental conditions: average ($\bar{T}_\infty$) and minimum ambient temperature ($T_{\infty,min}$), maximum natural snowfall intensity (I_s), 24-h accumulated snowfall precipitation (P), snow layer thickness (δ_{SL}), and the area density of the snow layer (m''_{SL}).

Test No.	$\bar{T}_\infty$ (°C)	$T_{\infty,min}$ (°C)	$I_{s,max}$ (mm/h)	P (mm)	δ_{SL} (cm)	m''_{SL} (kg/m^2)	Fire (Y/N)
Base case (no Snow)	-8.7	-10	0	0	0	0	Y
SF1-SF3	-8.5	-17.3	1.1	5.1 (heavy)	N.A.	N.A.	Y
SF4-SF6	-2.6	-6.7	0.9	7.9 (heavy)	N.A.	N.A.	Y
SF7	-3.8	-6.7	0.5	1.1 (light)	N.A.	N.A.	Y
SL1	-11.7	-18.2	0	0	3	8.0	Y
SL2	-3.5	-12.9	0	0	3	8.3	Y
SL3	-4.1	-12.6	0	0	4	12	Y
SL4	-0.9	-8.7	0	0	6	16	Y
SL5	-5.1	-9.5	0	0	7	18	Y
SL6	-1	-8.9	0	0	8	20	N
SL7	-8.7	-10	0	0	8.5	22	N
SL8	-6.6	-10.9	0	0	10	26	N
SL9	-5.1	-9.5	0	0	10	27	N
SL10	-6.8	-8.1	0	0	10	25	N
SL11	-6.5	-11	0	0	12	30	N
SL12	-7.1	-14.1	0	0	15	42	N
SL13	-6.9	-12.4	0	0	17	48	N

(II) Effect of accumulated snow layers (SL tests) on smouldering peat fires. All snow samples were collected right after the natural snowfall. In the experiment, the peat fire was first ignited on the ground without covering any snow. About 2 min after the ignition heating, a snow layer with a given thickness (δ_{SL}) from 1 cm to 20 cm was placed on the surface. The thickness of the snow layer was controlled, and several 20 cm × 20 cm snow-layer samples were collected and weighed to calculate its surface density. To reduce the effect of snow metamorphism in natural environment, all the snow used in this work was freshly fallen within three days, so that the bulk density was well controlled (ρ_{SL} = 265 ± 20 kg/m^3). After each fire test, fuel residues were collected to determine the burning mass loss and the residual moisture content. More test details are summarised in Table 2.

(III) Large demonstrations. To better validate the observations in small-scale experiments, larger demonstrations with both natural snowfall and accumulated snow layer were performed on the same field. The burning area was designed to be 1.5 m × 1.5 m. The depth of area mainly ranged from 15 cm to 20 cm, with depth of only 5 cm on limited parts due to on-site reasons (e.g., difficulty in permafrost excavation). The large demonstrations employed the same peat soil and ignition protocol as the small-scale experiments, but the ignition was limited to a corner of this area (15 cm × 15 cm). The fire was initiated during a natural snowfall ($I_{s,max}$ = 0.7 mm/h; P = 2.6 mm), and due to the large dimension of this area, natural snow accumulation occurred in the regions where the peat fire had not yet spread. Therefore, both the effects of natural snowfall and snow accumulation could be observed and discussed in this demonstration.

3. Results and discussion

3.1. Underground peat fire phenomena

3.1.1 Fire without snow (base case)

Our previous laboratory experiments have revealed that the fire threshold of dry peat could be lower than -45 °C, when the peat moisture content was close to zero (Lin et al., 2021b). These fire experiments were performed inside a reactor made of ceramic insulation boards, which minimised the heat loss and removed the oxygen supply in the lateral direction. Therefore, we first validated these peat fire behaviours in real soil land under a cold environment.

Fig. 2a-b describes a snapshot and a temperature evolution of a baseline experiment without any snow intervention (snowfall or accumulated layer), where the average ambient temperature during the test was measured to be about -8.5 °C. Once ignited from the top surface, peat fire successfully propagated downwards to the bottom in around 16 h. Meanwhile, a thin black char layer was observed on the top free surface that was not burnt completely into the white ash because of a larger environmental cooling (Huang and Rein, 2017). Such a char layer may act as an insulation layer to decrease the ambient heat loss from the deeper layers, leading to a higher peak smouldering temperature right below the char layer (e.g., ~ 300 ºC at -5 cm vs. ~ 400 ºC at -15 cm). Afterwards, near the end of the fire spread, the measured temperature near the bottom was about 200 ºC where the smouldering front could no longer propagate downwards, leaving the other black char layer. At about 20 h, the underground smouldering fire burnt out, and a mixture of unburnt chars, ashes, and undisturbed peat could be observed in the pit.

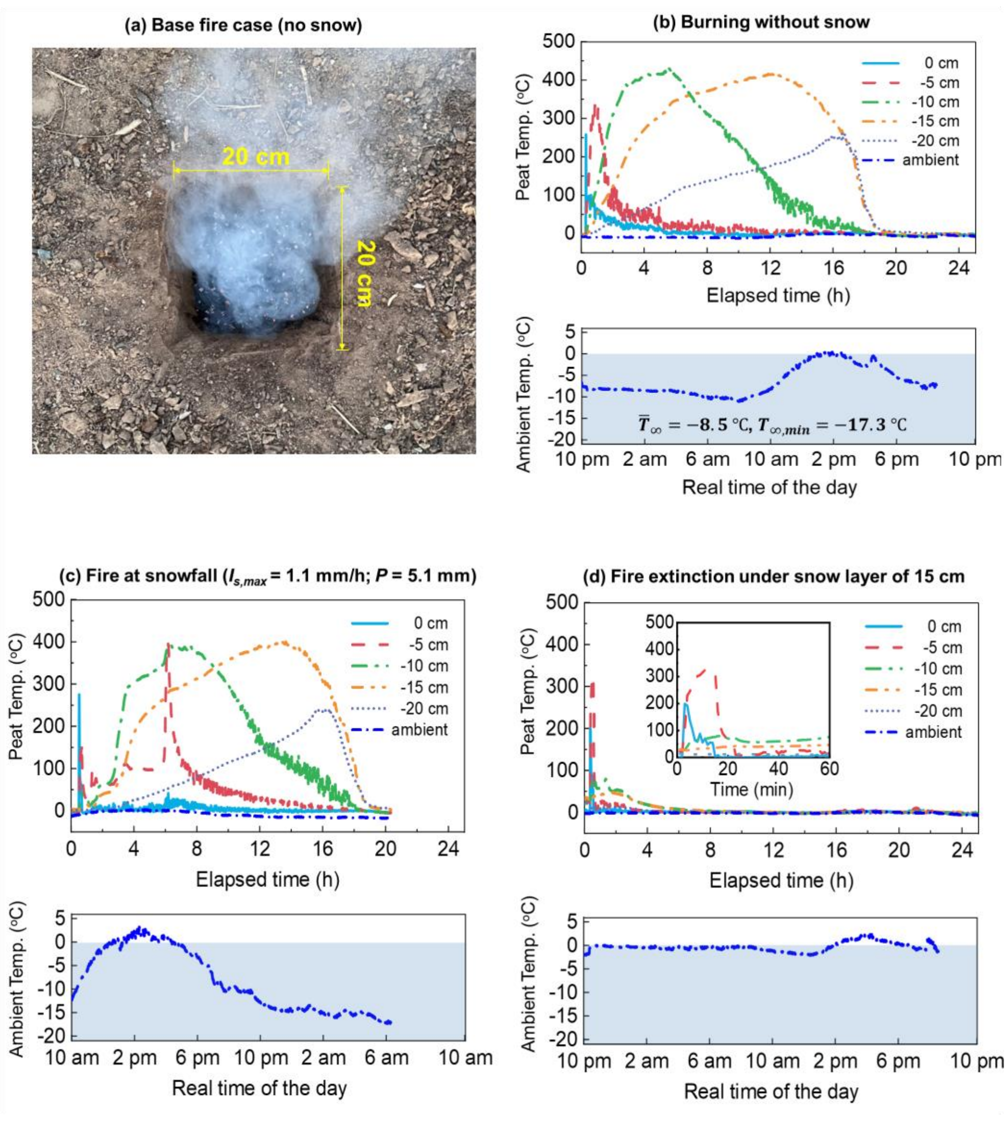


Fig. 2. (a) A photo showing the formation of an unburnt char layer on the top peat soil surface, and thermocouple measurements of (b) burning peat samples without the intervention of snow, (c) a failed fire

suppression by a heavy natural snowfall ($I_{s,max}$ = 1.1 mm/h; P = 5.1 mm), and (d) successful fire suppression by a 15-cm thick snow layer, as well as their ambient temperatures throughout the burning process.

3.1.2 Fire with a natural snowfall (SF)

Fig. 2c shows the thermocouple measurements of a peat fire under a heavy natural snowfall ($I_{s,max}$ = 1.1 mm/h; P = 5.1 mm), and the corresponding burning process is shown in Fig. 3a by snapshots (please see the full video in the supplemental materials S1). In general, compared to Fig. 2b, the trend of fire propagation was only slightly influenced by the snowfall, except for the fire near the top surface. Therefore, such a snowfall was not able to suppress the smouldering peat fires. To be specific, when the snow reached the burning area, the temperature near the top surface (-5 cm) decreased and fluctuated, because the top peat layer was wetted, and the fire was partially and temporarily extinguished.

However, due to the strong evaporation and the water absorption in the upper soil layer, it was difficult for the melting snow to penetrate and arrive at the deeper soil layer. Therefore, the temperatures below the top layer (e.g., -10 cm and -15 cm) quickly increased to about 400 ºC, just like the base case in Fig. 2b. As the fire grew, the top peat layer was dried and burnt as well, and the entire peat sample was burned out eventually. Fig. 3b further compares the burning mass losses of three repeating tests under a heavy natural snowfall $I_{s,max}$ = 1.1 mm/h or P = 5.1 mm with those without snowfall. The burning mass loss fluctuates around 80% in both scenarios, showing negligible difference. This further demonstrates that a snowfall of $I_{s,max}$ = 1.1 mm/h or P = 5.1 mm cannot effectively extinguish the underground smouldering peat fire. This supports many field observations available in the Arctic-boreal peatland, where people see that the underground smouldering peat fires continue burning under a snowfall.

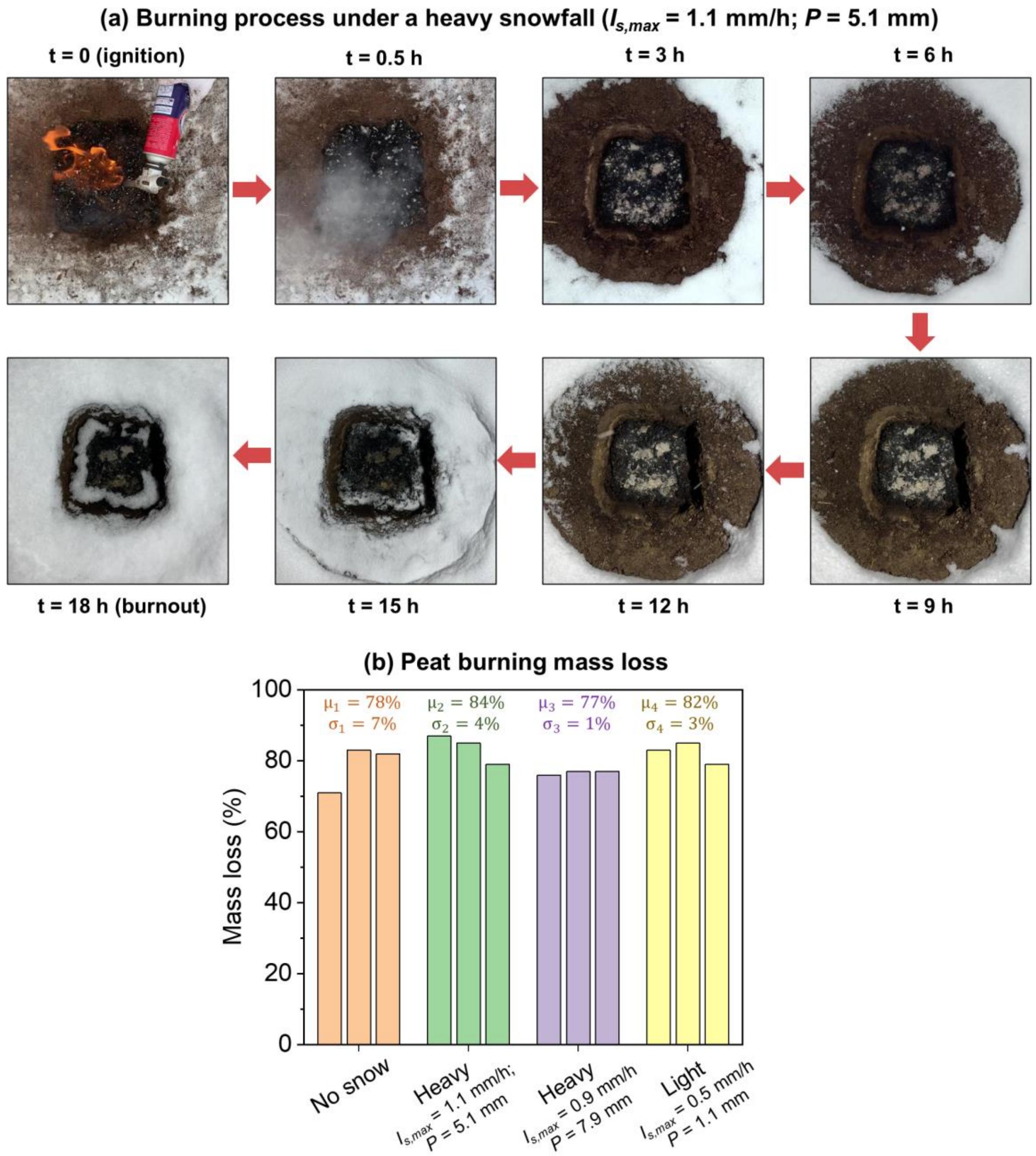


Fig. 3. (a) Snapshots of a burning process under a heavy snowfall of $I_{s,max}$ = 1.1 mm/h or P = 5.1 mm, where the original video could be found in Supplementary material Video S1. (b) comparison of burning mass loss without snowfall and under heavy or light snowfalls (μ and σ refer to the mean value and standard deviation).

3.1.3 Fire with accumulated snow layers (SL)

Fig. 2d further shows the temperature evolution of a peat fire where a 15-cm thick snow layer was placed on the top surface of the burning soil layer 2 min after the forced ignition. Firstly, the temperature at -5 cm increased to above 300 ºC, so that the fire was successfully ignited to sustain smouldering propagation. Shortly after, its temperature significantly decreased to ambient temperature, while the fire front no longer propagated downwards. The temperature measurements were continued for another 24 h, and no re-ignition was observed. Therefore, smouldering peat fire can be extinguished, if the accumulated snow layer was 15 cm. Fig. 4a shows another example where the peat fire was suppressed by a thick snow layer of 20 ± 1 cm, where some unmelted snow remaining on the ground was observed after the fire was extinguished. Further experiments found that the thickness of the remaining snow layer increased with the initial snow layer thickness. On the other hand, if the snow layer thickness was reduced (Fig. 4b), it eventually became too thin to extinguish the fire. Thus, by gradually adjusting the snow layer thicknesses, we can identify the threshold to suppress a peat fire.

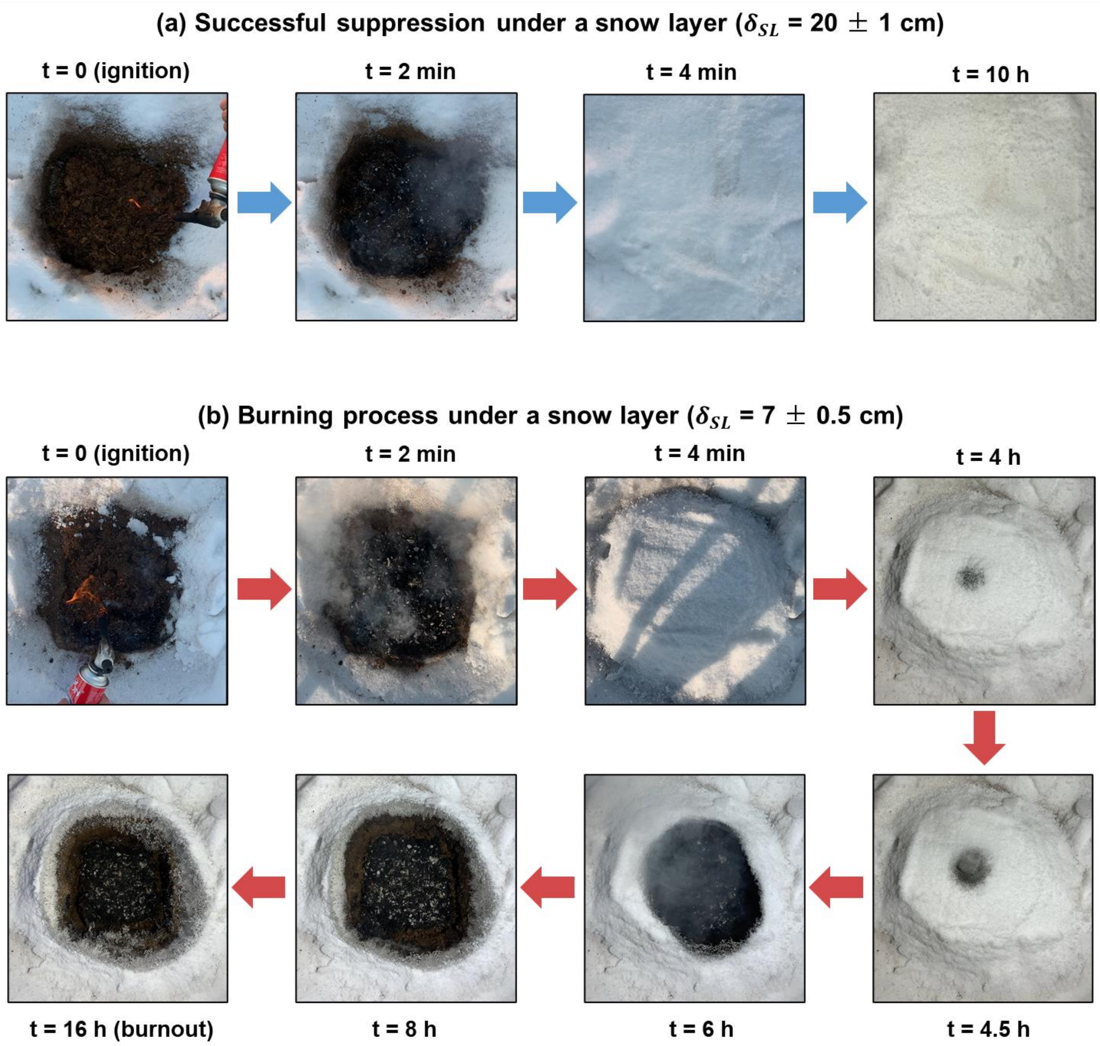


Fig. 4. Snapshots of (a) a successful fire suppression under snow layer (δ_{SL} = 20 ± 1 cm), and (b) burning under snow layer (δ_{SL} = 7 ± 0.5 cm). The original video: Supplementary material Video S2 and S3.

3.2. Threshold of peat fire under snow cover

Fig. 5 further summarises (a) dried burning mass losses of the peat soils and (b) moisture contents of the residues of different cases, where snow layers with different thicknesses were placed on the burning peat samples. There was a clear boundary at 8 cm, which could be defined as the minimum snow layer thickness to suppress a smouldering peat fire at a mean environment temperature of -5 ºC. If the thickness of the snow layer was smaller than 8 cm, the burning mass loss of peat remains relatively stable at ~ 75% (close to the mass loss without snow). As most of the melting water was evaporated by the hot smouldering front, the moisture content of residue remained below 20% for these cases. On the other hand, when the thickness of the snow layer was larger than 8 cm, the total mass loss dropped sharply to 10-35%, which was mainly caused by the ignition process. For these cases, the moisture contents of residues were higher than 60%, so that the heat released from the smouldering peat fire can still melt most of the snow layer.

On the other hand, the effect of the surface snow layer on suppressing the peat fire may be similar to the moisture content of peat. For simplicity, we assume that the surface peat layer completely absorbs the melting snow uniformly, so that the moisture content of peat will increase to

$$\mathrm{MC}_{p,SL} = \mathrm{MC}_{p,0} + \frac{\delta_{SL}\rho_{SL}}{\delta_p \rho_p} \tag{1}$$

where the subscript "p" and "SL" represent the peat and snow layer, respectively. For example, a 10-cm thick snow cover above a 20-cm thick dry peat ($\mathrm{MC}_{p,0} \approx 5\%$) can be regarded as 20-cm deep peat with MC = 96%.

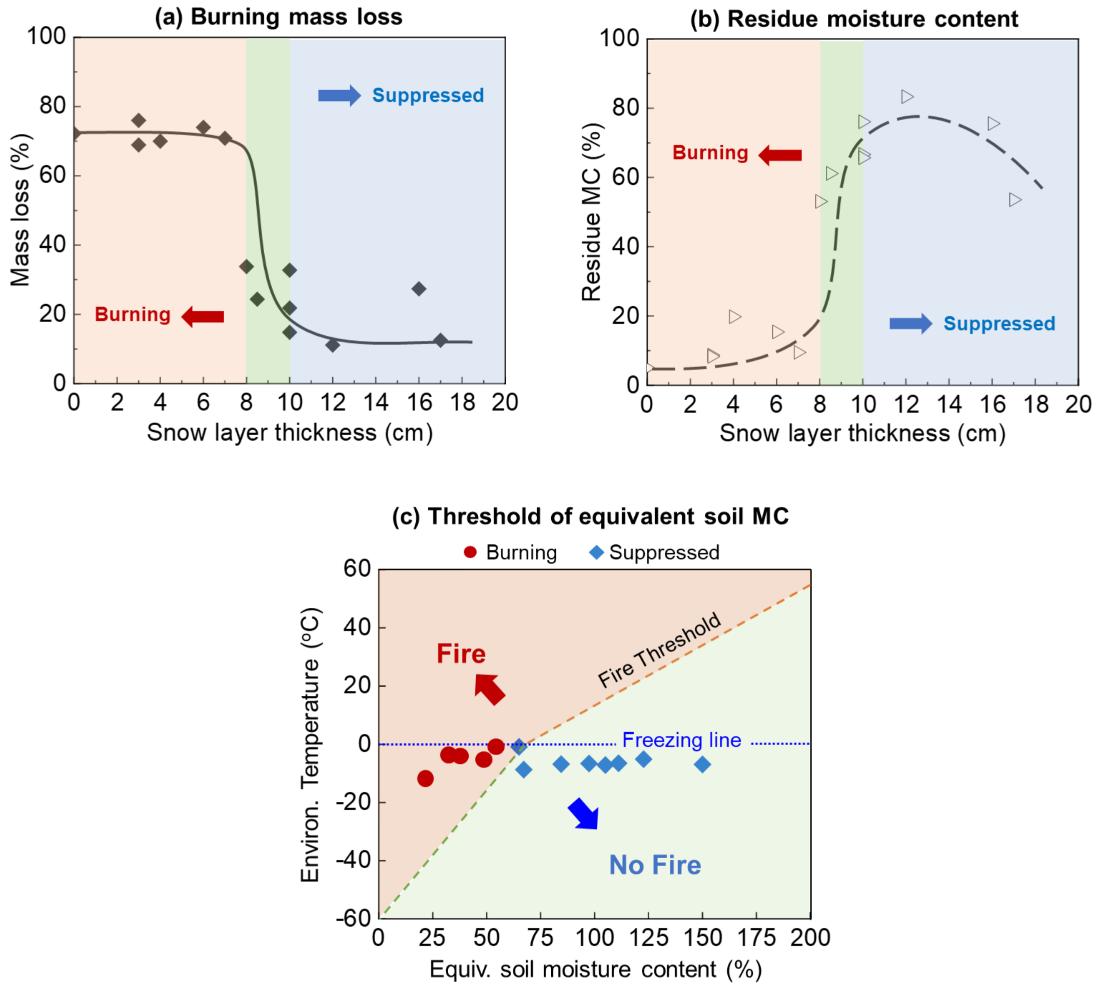


Fig. 5. (a) Mass loss of (dried) peat soil under different snow layer thicknesses. (b) Moisture content of burnt residue after smouldering peat fire with different snow layer thicknesses on the top surface, where the mean environment temperature is around -5 ºC. (c) Experimental data as a function of environmental temperature and equivalent soil moisture content, which agreed well with the curve of fire threshold obtained from previous lab tests (Lin et al., 2021b).

Based on this analogy, Fig. 5c summarises the experimental relationship between the environmental temperature and the equivalent peat moisture content, where the smouldering fire threshold ("Fire" and "No Fire" zones) found previously (Lin et al., 2021b) was included for analysis. For thin snow layers (< 8 cm) that were not able to suppress the peat fires, all of these burning cases are exactly located in the "Fire" zone (see Table 2). For thick snow layers (>8 cm), all extinguished cases are located in the "No Fire" zone. In other words, the effect of the snow layer on suppressing peat fire can be explained by an increased equivalent soil moisture content and the smouldering fire threshold. Furthermore, the concept of equivalent moisture content may be used to evaluate the underground fire risk where the peatlands are generally covered by a snow layer in the Arctic-boreal regions.

3.3. Fire suppression limit of equivalent precipitation

For the peat fire below the snow layer, the preheated ground and hot emissions can gradually melt the snow into liquid water that penetrates and cools the soil to suppress the peat fire (if the snow cover is thick enough). By considering the melting time of the snow layer, the fire-suppression effect is actually very similar to the snowfall. For example, if a snow layer of 480 g weight (equivalent water of 12 mm within the area of pit) is melted by peat fire in 2 hours, its equivalent snowfall intensity is 6 mm/h. Then, based on experimental observations and temperature data, we can get the equivalent snowfall intensity and equivalent liquid water depth for all snow-layer tests.

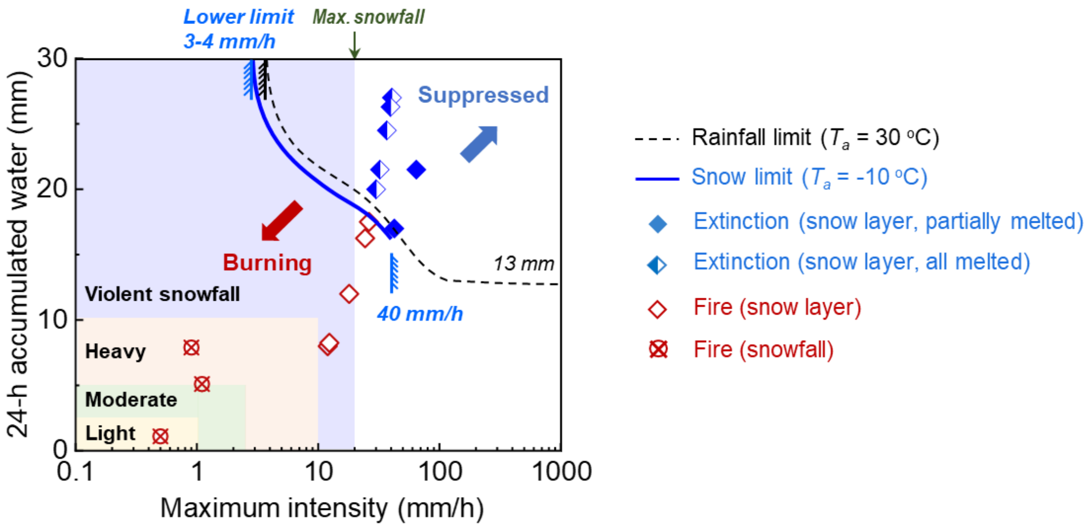


Fig. 6. Peat fire suppression limit of equivalent snowfall at -5 °C. The scattered points represent experimental data, while the solid curve represents a predictive limit. The limit of rainfall limit at the 30 °C tropical peatlands was extracted from (Lin et al., 2020).

Fig. 6 summarises the equivalent liquid water depth and precipitation intensity for all snowfall and snow-layer tests (see all markers). First, we found that the melting rate of snow increases with the thickness of the snow layer, because a thicker snow layer can absorb the heat of fire emission more efficiently. Nevertheless, by further increasing the snow layer above 12 cm, it can extinguish the underground peat fire before it is fully molten so that its equivalent snowfall intensity starts to decrease. Then, there is a maximum equivalent snowfall intensity for the snow layer, which is found to be about

40 mm/h at the testing ambient temperature of -5 ^{o}C. Note that this maximum value changes with the ambient temperature, and it is much larger than the historical maximum natural snowfall of around 20 mm/h (Angela Fritz, 2015).

Although the limited numbers of snowfall and snow-layer test data cannot conclude a full fire-threshold curve. Nevertheless, such a limiting curve should follow a similar trend to that for rainfall. By referring to the rainfall limit previously measured in a 30 ^{o}C lab environment (Lin et al., 2020), we can plot a similar fire-threshold curve for snowfall in Fig. 6. This snowfall curve should be lower than the rainfall curve, because of a lower environmental temperature (from -5 ^{o}C to -18 ^{o}C) and the additional heat of melting snow. The limiting curve is extended beyond 20 mm/h (i.e., the natural maximum snowfall) to 40 mm/h to include the suppression caused by the snow layer.

3.4. Theoretical analysis

3.4.1. Minimum snow layer thickness

To physically explain the suppression mechanism and limit of peat fires by snow covers, the energy balance between the accumulated snow layers and smouldering fires is simplified in Fig. 7a. When there is a snow layer above the underground peat fire, it will melt into water rapidly by the hot surface and the floating hot smoke from smouldering burning, so the melting water will penetrate downward and cool down the underground burning zone. As the snow layer thickness increases, eventually, the total heat released from underground peat fire can no longer overcome the cooling from the snow cover.

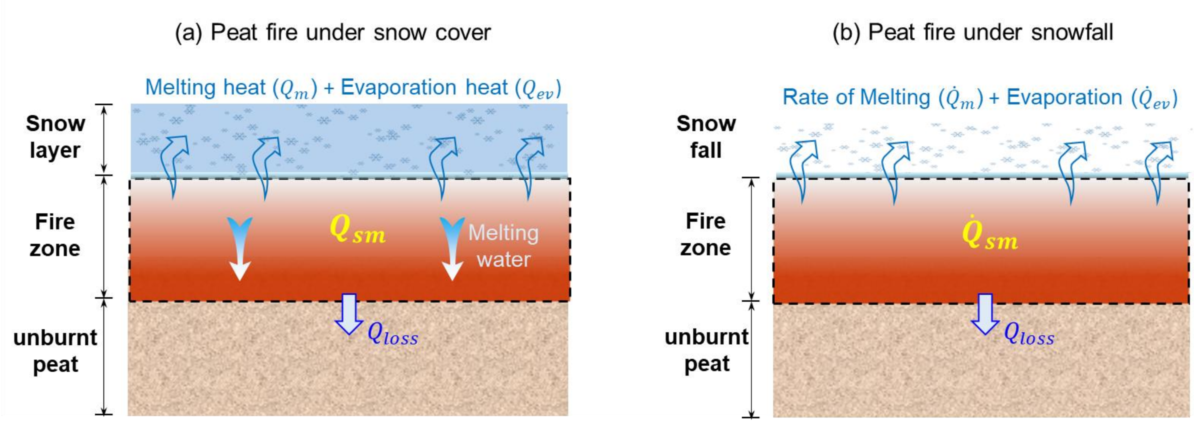


Fig. 7. Illustrations of snow-fire interaction: (a) peat fire with a minimum snow layer and (b) snowfall where all the snow is melted and evaporated directly on the surface by the hot burning zone.

Then, the simplified energy-conservation equation can be established among heat released from the current smouldering fire zone (Q_{sm}), energy storage in the preheated soil (Q_T), heat absorption by snow melting (Q_m) and the evaporation of molten water (Q_{ev}), and other heat losses (Q_{loss}) in Eq. (2) as

$$Q_{sm} + Q_T = Q_m + Q_{ev} + Q_{loss} \tag{2}$$

Since $Q_T \ll Q_{sm}$, it can be further specified as Eq. (3):

$$m_p'' \Delta H_{sm} = m_{SL}''(\Delta H_m + \Delta H_{ev}) + Q_{loss} \tag{3}$$

where $m_p'' = \delta_{sm}\rho_p$ is the burning mass of peat fire per area [kg/m^2], $\delta_{sm} \approx 10$ cm is the thickness of the underground smouldering fire front (Qin et al., 2022b), ρ_p is the density of dry peat, and ΔH_{sm} is the heat of smouldering combustion. For the snow layer, $m_{SL}'' = \delta_{SL}\rho_{SL}$ is the weight of accumulated snow layer per unit area, ΔH_m is the heat of snow melting, and ΔH_{ev} is the overall heat of water evaporation.

By further rearranging Eq. 3, the required minimum mass of the snow layer per area for fire suppression could be calculated as

$$m_{SL}'' = \delta_{SL}\rho_{SL} \geq \frac{m_p'' \Delta H_{sm}}{\Delta H_m + \Delta H_{ev}} \tag{4}$$

where the environmental heat loss and the melting water penetrating through the fire region are neglected. The burning flux is estimated to be m_p'' =4.0 ± 0.5 kg/m^2 in this work. Key parameters can be found in the literature, where $\rho_p = 145$ kg/m^3, $c_p = 2$ kJ/(kg-K), $\Delta H_{sm} = 16 \pm 4$ MJ/kg (Huang and Rein, 2016b), $\Delta H_m = 0.3$ MJ/kg, and $\Delta H_{ev} = 2.7$ MJ/kg (evaporate at 100 ℃). By neglecting other energy losses, the minimum mass of snow per area to suppress the smouldering peat fire can be calculated as $m_{SL}'' \approx 20$ kg/m^2. As the bulk density of the snow layer was measured to be $\rho_{SL} = 265$ kg/m^3, the minimum snow layer depth can be calculated as

$$\delta_{SL} = \frac{m_{SL}''}{\rho_{SL}} = \frac{20 \text{ kg/m}^2}{265 \text{ kg/m}^3} \approx 8 \text{ cm [snow]} \approx 20 \text{ mm [liquid water]} \tag{5}$$

which agrees well with the experiment observation of about 8 cm of snow layer (see Fig. 5a) and the equivalent minimum liquid water depth of about 20 mm in Fig. 6.

3.4.2. Minimum snowfall intensity

In the case of snowfall, the impact of snowfall precipitation is dynamic and different from the accumulated snow cover. To suppress the fire, the cooling rate of snow melting, and the subsequent water evaporation should be larger than the heat release rate from the smouldering front (see Fig. 7b). Then, we can use the time derivative of Eq. (3) and introduce the precipitation intensity ($I = d/\Delta t$)

$$\dot{m}_p'' \Delta H_{sm} = I_{min}\, \rho_w (\Delta H_m + \Delta H_{ev}) \tag{6}$$

where $\dot{m}_p''$ is the smouldering burning flux (burning mass loss rate per unit area) of peat soil. Therefore, the minimum (liquid water equivalent) snowfall intensity at a specific ambient temperature (I_{min}) is

$$I_{min} = \frac{\rho_p V_{min} \Delta H_{sm}}{\rho_w (\Delta H_m + \Delta H_{ev})} \tag{7}$$

where $V_{min} = \dot{m}_p''/\rho_p$ is the minimum smouldering fire spread rate, which was measured to be 0.5 ± 0.1 cm/h (Lin et al., 2022; Lin and Huang, 2021), and $\rho_w = 1000$ kg/m^3 is the density of water. Then, the minimum snowfall intensity is calculated to be 4 ± 1 mm/h (see Fig. 6). This explains the reason that even a long-lasting heavy snowfall in this experiment (1.1 mm/h) still cannot suppress a peat fire. Because the heat of melting snow is much smaller than the heat of evaporation, the minimum snowfall intensity for suppressing peat fire should be comparable to that of rainfall.

3.5. Large-scale demonstrations

Scaling up the small-scale fire tests to a larger field test is important to understand the real wildfire process. Fig. 8 shows snapshots of some key phenomena during the large demonstrations under natural snowfall ($I_{s,max}$ = 0.7 mm/h; P = 2.6 mm), and the original video can be found in Supplementary material Video S4. Initially, the peat soil was ignited for 2 minutes in a small area (15 cm × 15 cm) at the corner (Fig. 8a). After ignition, the peat fire started to spread outwards in a fan-shaped pattern, while natural snowfall caused snow accumulation in the undisturbed areas (Fig. 8b). After 20 hours, fire still existed and the burning area expanded, confirming that this peat fire was not extinguished by this natural snowfall. This well agrees with the experimental observations in small-scale tests. Meanwhile, snow began to accumulate on the surface of the trailing edge of the fire front that had been burned out (Fig. 8c). Afterwards, the leading edge of the fire front began to break up into separated fronts without consuming all the fuel in a finger-like manner (Fig. 8d). A possible reason is that the peat layer at these locations is relatively shallow (measured as ~ 5 cm) which cannot generate enough heat to overcome the heat loss caused by the snow (Lin et al., 2021c). Finally, the fire burnout and the fire lasted for 40 hours in total (Fig. 8e). This large-scale experiment provided more information on the progression of smouldering peat fires under natural snowfall and accumulated snow layers. More and larger-scale field experiments under different environmental conditions (e.g. wind, moisture content, snowfall, and topography) are needed to unravel the complex relationship between fire and snow in real peatlands.

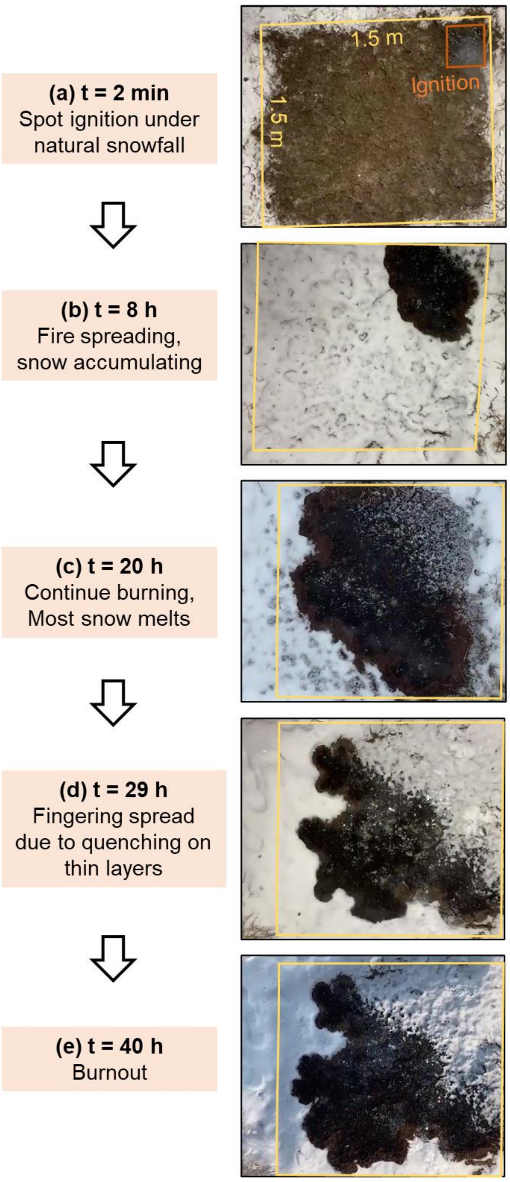


Fig. 8. Snapshots of some key fire phenomena of the large demonstration under natural snowfall ($I_{s,max}$ = 0.7 mm/h; P = 2.6 mm). The original video can be found in Supplementary material Video S4.

4. Conclusions

In this work, experiments were applied to investigate the effects of natural snowfall and snow cover (layer) on the smouldering peat fires in the shallow soil layer. Experiments were conducted outdoors in Inner Mongolia, China, with a local average ambient temperature below the freezing point (0 ºC) to simulate the fire environments in the Arctic-boreal regions. Two independent series of experiments were conducted to investigate the effect of (I) natural snowfall (SF) and (II) accumulated snow layers (SL) with a thickness of up to 20 cm on the development of smouldering peat fires.

We found that a natural snowfall with a maximum water-equivalent intensity of 0.9 mm/h or 24-h total precipitation of 7.9 mm (heavy snow) was not able to suppress a shallow smouldering peat fire. This was consistent with the observation of over-wintering "zombie fire" in the Arctic-boreal regions, where the underground smouldering hot spots can still be sustained in the snowy winter.

On the other hand, a thick snow cover on the peat surface can extract heat from the burning front underneath, and the minimum thickness of the snow layer to successfully extinguish the peat fire was found to be around 9 ± 1 cm, consistent with the theoretical analysis. Furthermore, the system of dry peat with surface snow cover could be simplified as wet peat after completely absorbing the melting snow, and its equivalent moisture content could be used to evaluate its fire risk referring to the ignition map from (Lin et al., 2021b). Afterwards, a large-scale experiment (1.5 m × 1.5 m) in the same field was conducted to validate the small-scale experimental phenomena, and a finger-like fire spread manner was also observed.

Due to the lower ambient temperature and additional heat of melting snow, the limiting conditions of peat fire suppression by precipitation in Arctic-boreal regions were predicted to be lower than those in tropical regions. This work demonstrates the existence of overwintering wildfires in the Arctic-boreal regions and helps evaluate the impact of snow on the development of peat fires. Future works will focus on enriching the fire detection and protection strategies for fighting smouldering wildfires in cold regions.

Declaration of Competing Interest

The authors declare that there is no conflict of interest.

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CRediT Authorship Contribution Statement

Yunzhu Qin: Investigation, Data Curation, Formal analysis, Writing-original draft, Resources. **Yichao Zhang**: Investigation, Formal analysis, Resources. **Shaorun Lin**: Data Curation, Methodology, Formal analysis, Writing-review & editing, Resources. **Yang Shu**: Supervision, Resources. **Yuhan Huang:** Writing-review & editing. **Xinyan Huang:** Conceptualization, Supervision, Methodology, Formal analysis, Writing-review & editing, Funding acquisition. **Mei Zhou:** Supervision, Resources.

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