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Mitigating smoldering peatland fire via buried heat pipes: a new concept of underground firebreak

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ABSTRACT

Background. Smoldering underground fires in peatlands are among the most persistent and destructive wildfire types, but resisting conventional suppression methods. **Aims.** This study experimentally evaluates a heat-pipe-based underground firebreak concept as a passive cooling strategy to mitigate smoldering propagation in stratified peat profiles. **Methods.** Laboratory-scale experiments were conducted with an upper dry peat layer overlying a saturated layer. Heat pipes of varying lengths, geometries and quantities were installed with the condenser section positioned at the dry–saturated interface. **Key results.** Under these conditions, heat pipes reduced peak smoldering temperatures and, in some configurations, quenched combustion. The intervention expanded the high-moisture, non-combustible region ('safe zone') more than fivefold compared with control tests. Longer pipes and configurations with larger condenser surface areas demonstrated greater thermal suppression effects. **Conclusion.** The results provides a laboratory-scale proof of concept that heat pipes can function as passive thermal sinks and promote moisture redistribution at the dry–saturated interface in peat columns. **Implications.** These findings are limited to controlled laboratory experiments. Substantial additional experimental, modeling and field research are required before assessing real-world deployment potential.

Keywords: firebreak, firefighting technologies, fire suppression, heat transfer, peatland fire, smoldering combustion, underground fire, water table.

Introduction

Peat is an organic-rich soil formed from the partial decomposition of plant materials under waterlogged, acidic and anaerobic conditions (Dargie *et al.* 2017; Swails *et al.* 2024). Despite occupying only ~3% of the Earth's land surface, peatlands serve as crucial terrestrial carbon reservoirs, storing approximately one-third of the global soil carbon, an amount comparable with the carbon stored in all living vegetation and the atmosphere (Gorham 1994; Turetsky *et al.* 2015; Gao *et al.* 2016; Rein and Huang 2021; Serk *et al.* 2022). Beyond their carbon storage capacity, peatlands also support high biodiversity and play a vital role in regional hydrological stability (Page *et al.* 2011; Huang *et al.* 2016; Musa *et al.* 2024; Zhang *et al.* 2025).

However, these ecosystems are increasingly vulnerable to wildfires driven by climate change, land-use change, population pressures and forest fragmentation (Rein 2013; Lin *et al.* 2021*a*; Zolkos *et al.* 2024; Cong *et al.* 2025; Qin *et al.* 2025; Yang *et al.* 2025). In particular, smoldering wildfires in peatlands are renowned as one of the largest (in terms of fuel consumption) and longest-lasting (for weeks or months) fire phenomena on Earth (Rein 2013), consuming deep soil layers and releasing substantial quantities of carbon into the atmosphere (Heil and Langmann 2004; Poulter *et al.* 2006; See *et al.* 2007; van der Werf *et al.* 2010; Gaveau *et al.* 2014; Aurell *et al.* 2016; Mickler *et al.* 2017; Lin *et al.* 2021*b*; Santoso *et al.* 2022; Li *et al.* 2025). Global emissions from peatland fire in boreal–arctic and tropic regions have been estimated to reach up to 15% of annual fossil fuel emissions, rivaling the total anthropogenic emissions from the European Union (Gorham 1994; Page *et al.* 2002; Poulter *et al.* 2006; Turetsky *et al.* 2015; Sazawa *et al.* 2018; Lin *et al.* 2021*b*; Rein and Huang 2021; Chen *et al.* 2025). Moreover, large-scale peat fires produce persistent transboundary haze, with severe impacts on air quality, human health and regional economies (Gaveau *et al.* 2014; Hayasaka *et al.* 2014; Hu *et al.* 2018, 2020). Therefore, proactive fire management, including prevention, early detection, suppression and post-fire recovery, is critical owing to the nonrenewable nature of peat and its significant fire hazards to the environment (Atwood *et al.* 2016; Page and Baird 2016; Wilkinson *et al.* 2018; Goldstein *et al.* 2020).

Owing to their subsurface nature and persistence (Qin *et al.* 2022*b*), peat fires are notoriously difficult to suppress, especially when the combustion front penetrates below the peatland surface (Ramadhan *et al.* 2017; Lin *et al.* 2020; Mulyasih *et al.* 2022; Qin *et al.* 2022*b*). These fires have been observed to survive and hibernate below a snow-cover layer and revive on the surface the following spring, and are known as 'overwinter fire' (Scholten *et al.* 2021; Qin *et al.* 2025). The dynamics of smoldering peat fires are controlled by the coupled transport of heat, oxygen and moisture (Huang and Rein 2017; Yang *et al.* 2019; Qin *et al.* 2022*a*, 2024*a*, 2024*b*; Song 2022). Within the reaction zone, temperatures typically range between 400 and 700°C, sufficient to sustain slow pyrolysis and oxidation of organic matter even under limited oxygen availability (Huang and Rein 2016; Yang *et al.* 2019; Qin *et al.* 2022*a*). The thermal gradient established ahead of the front drives drying and preheating of adjacent peat layers, creating a positive feedback that allows the smoldering front to propagate downward and laterally (Chen *et al.* 2015). Propagation is characteristically slow, on the order of millimeters to centimeters per hour (Chen *et al.* 2015; Yang *et al.* 2016, 2019; Huang and Rein 2017; Lin and Huang 2021; Yin *et al.* 2023), yet this low velocity enables persistence over weeks to months (Qin *et al.* 2022*b*; Santoso *et al.* 2022). Depth of burning is also strongly dependent on peat bulk density, porosity and water table level (Benscoter *et al.* 2011); in drained or drought-affected systems, combustion can extend to depths exceeding 1 m (Lukenbach *et al.* 2015), leading to long-term carbon loss and severe ecological damage (Ballhorn *et al.* 2009; Turetsky *et al.* 2015; Yustiawati *et al.* 2015; Mickler *et al.* 2017; Hugelius *et al.* 2020; Witze 2020; Qin *et al.* 2022*b*).

Moisture content is the primary factor limiting fire severity: when water content exceeds a critical threshold, typically 110–130% on a dry-mass basis, the high heat capacity and latent heat of vaporization of water suppress temperature rises and prevent sustained oxidation (Prat *et al.* 2015; Prat-Guitart *et al.* 2016; Rein *et al.* 2017; Dadap *et al.* 2019; Prior *et al.* 2024). Conversely, when peat dries below this limit, smoldering is self-sustaining because heat released by oxidation is sufficient to offset conductive and evaporative losses. Quenching mechanisms therefore rely on disrupting this energy balance, most commonly by elevating moisture above the critical threshold through flooding or rewetting (Ratnasari *et al.* 2018; Lin *et al.* 2020; Santoso *et al.* 2021, 2022), or alternatively by reducing fuel load (i.e. energy release) via physical barriers or firebreaks (Lin *et al.* 2021*a*). However, water infiltration into deep subsurface layers is often limited by hydrophobicity, compaction and preferential flow (Lukenbach *et al.* 2015; Perdana and Ratnasari, 2018; Wu *et al.* 2020), which explains why conventional suppression methods frequently fail to extinguish underground peat fires.

Soil moisture is also closely linked to the water table level (Watts 2012; Huang *et al.* 2015; Prat-Guitart *et al.* 2016; Dadap *et al.* 2019). However, human activities such as canal construction for agriculture or logging often lower the water table, increasing fire susceptibility (Turetsky *et al.* 2015; Wilkinson *et al.* 2018; Taufik *et al.* 2019). In response, hydrological interventions like canal blocking, artificial rewetting (e.g. via water bombing, tube wells, or water injection) and firebreak canals have been adopted across southeast Asia to restore water levels and limit fire spread. Yet these strategies are labor-intensive, resource-demanding and often insufficient under prolonged drought conditions, which continue to accelerate peat drying and promote fire ignition.

To address these limitations, innovative passive prevention technologies are needed. One promising but unexplored approach involves the use of buried heat pipes, which are high-efficiency, passive thermal devices capable of transporting heat through evaporation–condensation cycles without external energy input (Jouhara *et al.* 2017). Widely used in electronics, aerospace and air-conditioning systems, heat pipes could offer a novel solution for subsurface fire mitigation. As illustrated in Fig. 1, heat pipes embedded vertically in the peat soil profile could absorb heat from a near-surface smoldering front (via the evaporator section), transfer it downward toward the saturated zone (the condenser) and enhance water evaporation. The water vapor could then migrate upward and condense in drier upper soil layers, potentially increasing peat moisture and inhibiting fire propagation. Despite the theoretical potential, no prior study has investigated the application of buried heat pipes in the context of peat fire suppression or underground firebreaks.

This study aims to experimentally evaluate the feasibility of using buried heat pipes as a passive fire mitigation tool in smoldering peatlands. Through a series of controlled laboratory-scale experiments, we explore their capacity to alter smoldering fire behaviors and promote the formation of 'safe zone' or an effective firebreak that prevents underground fire spread. We also discuss the influence of water table maintenance and hydrological interventions (such as firebreak canals) in the effectiveness of heat-pipe firebreaks and explore the potential of such a novel strategy for enhancing peatland resilience under increasing wildfire risk. This study represents the first experimental demonstration of buried heat pipes functioning as a subsurface firebreak system for smoldering peat fires, differentiating it

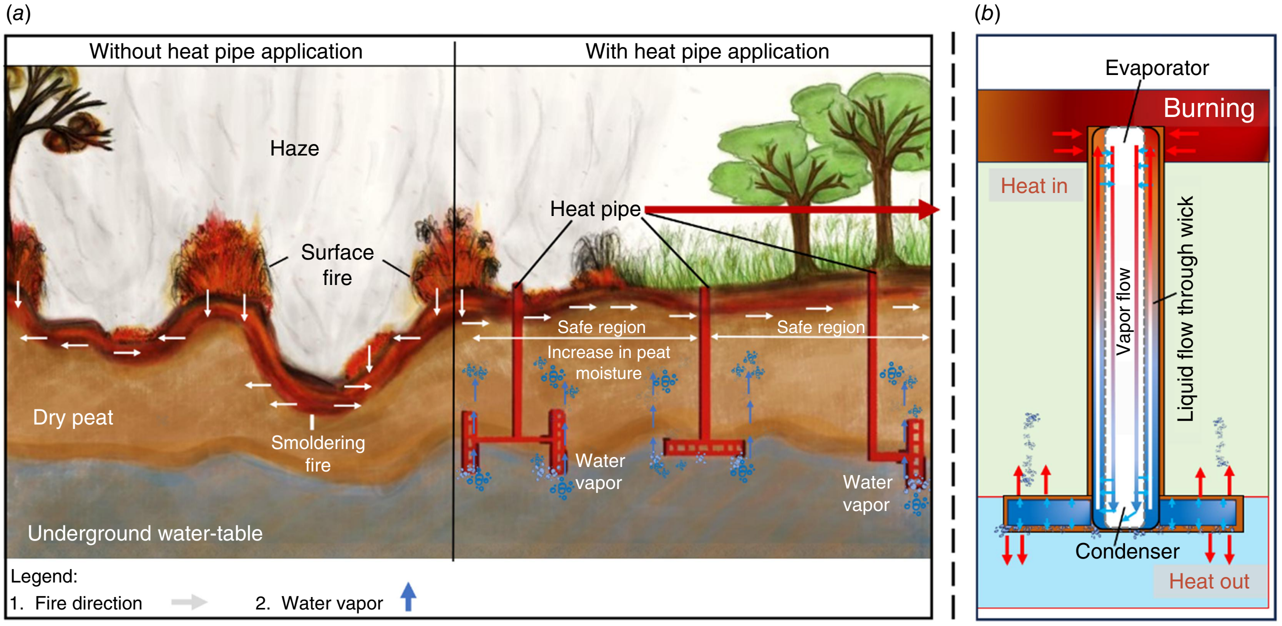

Fig. 1. (*a*) Illustration of buried heat pipe application in natural peat swamps as part of early fire prevention during the dry season; (*b*) mechanism of firefighting heat pipe for underground fires.

from existing hydrological restoration or active suppression methods.

Materials and methods

Preparation of peat samples

A cultivated commercial moss peat with high organic content (~97%), uniform dry bulk density (150 ± 10 kg/m^3) and consistent particle size was used in this study. This moss peat has been widely applied in previous research owing to its reliability and reproducibility under controlled conditions (Lin *et al.* 2019; Lin *et al.* 2021*a*, Lin *et al.* 2021*b*; Qin *et al.* 2022*a*, 2022*b*; Lin *et al.* 2024; Zhang *et al.* 2024). Before experimentation, peat samples were oven-dried at 90°C for 48 h to eliminate residual moisture. Dried samples were then stored in airtight containers to prevent moisture reabsorption from ambient air.

Peat soils are highly susceptible to smoldering during periods of low surface moisture (Wilkinson *et al.* 2020), whereas underlying saturated layers act as natural heat and moisture sinks. This condition commonly occurs in peatlands, where the upper layers may dry during drought or fire seasons while the deeper layers remain waterlogged owing to groundwater supply. To replicate this natural stratification of the water table, a two-layer system was prepared: an upper dry peat layer (above the water table and dried in ambient conditions) and a lower saturated peat layer (below the water table), as illustrated in Fig. 2*a*.

The dry layer was produced by allowing oven-dried peat to equilibrate under ambient conditions until it reached a target moisture content of 10 ± 5 wt-% (dry mass basis, i.e. the mass of water is 10% of the mass of dry soil). The saturated layer was prepared by fully immersing peat samples in water until achieving 900 ± 50 wt-% moisture content (dry-mass basis). During experiments, additional water was periodically supplied to maintain the water table and saturation of the lower soil layer throughout the test.

Heat pipe

The heat pipes used in this study were copper-based, passive thermal devices that transfer heat via phase-change processes involving the evaporation and condensation of an internal working fluid. Copper was selected owing to its high thermal conductivity and its widespread use in commercial heat pipes, making it suitable for controlled laboratory studies. As shown in Fig. 1*b*, heat is absorbed at the heated end (evaporator), causing the working fluid to evaporate; the resulting vapor travels to the cooler section (condenser), where it condenses and releases latent heat. The condensed fluid then returns to the evaporator by capillary action or gravity.

Owing to their high thermal efficiency and energy-free operation, these heat pipes are particularly suited for subsurface cooling applications. Three geometric configurations were fabricated: (1) L-shaped, (2) T-shaped, and (3) H-shaped (a dual L-shaped assembly designed for enhanced heat dissipation). Note that L-, T- and H-shaped pipes used in this study were custom-fabricated rather than standard commercial configurations. These geometries were chosen to systematically vary the condenser surface area and spatial

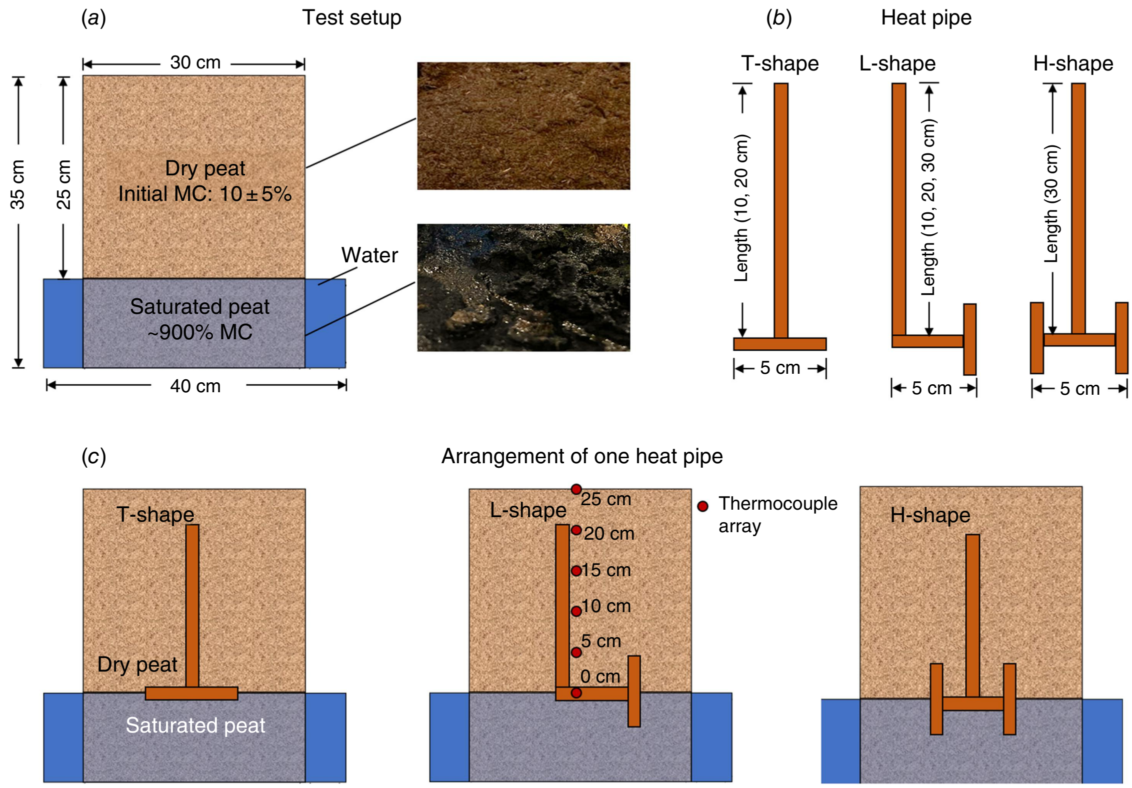

Fig. 2. (*a*) Experimental rig to simulate water table, upper air-dried peat and lower saturated peat; (*b*) three types of heat pipe design used in experiments; and (*c*) the arrangement of heat-pipe firebreak and thermocouple locations. The peat moisture content (MC) is represented on a dry soil mass basis.

heat interception characteristics, allowing us to examine how pipe geometry influenced cooling performance and safe zone formation. All pipes had a constant equivalent diameter of 5 mm. Three lengths of heat pipe were selected: 10, 20 and 30 cm, as shown in Fig. 2*b*.

Experimental design and set-up

In natural peatlands, the subsurface layers near the water table remain moist and are less prone to ignition. These zones, termed 'safe zone', are sustained by capillary water uptake and help prevent fire propagation. Therefore, this safe zone can be approximated as a natural firebreak that prevents the further downward (in-depth) propagation. To quantify the thickness of this region, a preliminary test was conducted without heat pipes. A cylindrical peat column (30 cm diameter × 35 cm height) was prepared and placed in a water-filled basin (40 cm diameter × 10 cm depth). The combustion container was made of perforated stainless steel, which allowed water from the external basin to infiltrate the lower peat layer through lateral and bottom openings. This design ensured realistic capillary rise and saturation consistent with natural peat hydrology. Afterwards, the sample was left to stabilize for over 24 h before ignition.

To simulate fire ignition, a 50 g batch of pre-ignited peat was placed at the top of the peat column and allowed to smolder for 5 min. This was followed by the addition of a 100 g peat layer (approximately 1.5–2.0 cm increased height) on the top of smoldering zone to reduce ambient heat loss, promote strong ignition and minimally affect deeper hydrological and thermal behavior. The underground temperature evolution was monitored using six K-type thermocouples (1 mm bead diameter) inserted at 5 cm vertical intervals along the column. Subsequently, to evaluate the role of heat pipes in suppressing smoldering fire and enhancing the safe zone, the cooler section (condenser) of the heat pipe was embedded at the interface between the saturated and air-dried peat layers, as depicted in Fig. 2*c*.

The experiments were designed to evaluate the capacity of buried heat pipes to reduce subsurface temperatures, limit fire spread and increase the soil moisture above the water table via localized heating and condensation. After the experiments, the peat remaining above the water table was collected and its moisture content was measured by gravimetric oven-drying at 105°C, following standard soil-science protocols.

To investigate the effect of the number of heat pipes, the heat pipe number was varied from one to three. For the two-pipe configuration, the pipes were positioned along the same horizontal diameter of the cylindrical peat column, symmetrically located on opposite sides of the center and placed at the midpoint of the radius. For the three-pipe configuration, the pipes were arranged at 120° intervals around the column, again positioned at the midpoint of the radius to ensure uniform spacing and comparable heat-transfer conditions. These configurations allowed us to assess the effect of adding additional pipes without introducing bias from pipe clustering or uneven radial distances. It should be emphasized that the multi-pipe configurations implemented in the 30-cm-diameter column correspond to pipe spacings that would likely exceed realistic field densities in natural peatlands. These tests were not designed to simulate deployable layouts, but rather to examine mechanistic sensitivity within a confined geometry, specifically, to probe upper-bound pipe–pipe thermal and vapor-flux interactions and their influence on safe zone thickness and peak temperature suppression. Increasing pipe number in the laboratory column effectively reduces spacing to levels that move in the opposite direction from feasible field implementation. Accordingly, the results should be interpreted as illustrating interaction limits under controlled conditions rather than providing operational guidance. Field-scale pipe density optimization, accounting for hydrological variability, durability and logistical feasibility, remains beyond the scope of this study and warrants dedicated future investigation.

For each set of experimental conditions, at least three repeat tests were performed to minimize test uncertainty. During the experiments, the ambient temperature was fixed at 25°C, the relative humidity was 50% and the ambient pressure was 101.3 kPa.

Results and discussion

Temperature profile and safe zone

This section presents the thermal and physical responses of stratified peat layers under smoldering fire conditions, emphasizing the effects of heat pipe integration on temperature regulation and safe zone formation. Two representative temperature profiles (one without heat pipe and one with a 10-cm long heat pipe) are first compared in Fig. 3 to illustrate the influence of thermal control on fire behavior. Note that the temperature at the 25-cm thermocouple indeed started near the ambient value of approximately 25°C, but increased very rapidly immediately after ignition was applied at the top surface. Because the smoldering front developed quickly during the initial ignition phase, the first recorded data point already reflected this sharp early heating, giving the appearance of a high 'initial' temperature.

In the control experiment without heat pipe, the smoldering front propagated steadily through the dry peat layer, reaching peak temperatures of approximately 500°C at a depth of 10–15 cm (Fig. 3*a*). This high thermal intensity facilitated continuous downward combustion into deeper layers. In contrast, when a heat pipe was introduced, peak temperatures were significantly reduced to 200–250°C at the same depths (Fig. 3*b*). Such a temperature reduction of 250–300°C clearly demonstrates the heat pipe's capacity to extract and redistribute heat away from the smoldering front.

Following the thermal analysis, the study focuses on the development of a 'safe zone' or 'natural firebreak', a distinct unburnt zone formed between the dry and saturated peat layers. This layer acts as a moisture barrier that can effectively inhibit downward fire spread and quench combustion. In the baseline experiments (without heat pipe), the safe zone emerged consistently between the ash-char layer and the saturated peat (Fig. 4). It was originally composed of dry peat with an initial moisture content of 10%, but during combustion, this layer absorbed significant amounts of moisture (primarily in the form of upward-moving vapor from the saturated layer), leading to a final moisture content of 250–400% (dry basis). Such a moisture enrichment prevented the smoldering fire from propagating further downward.

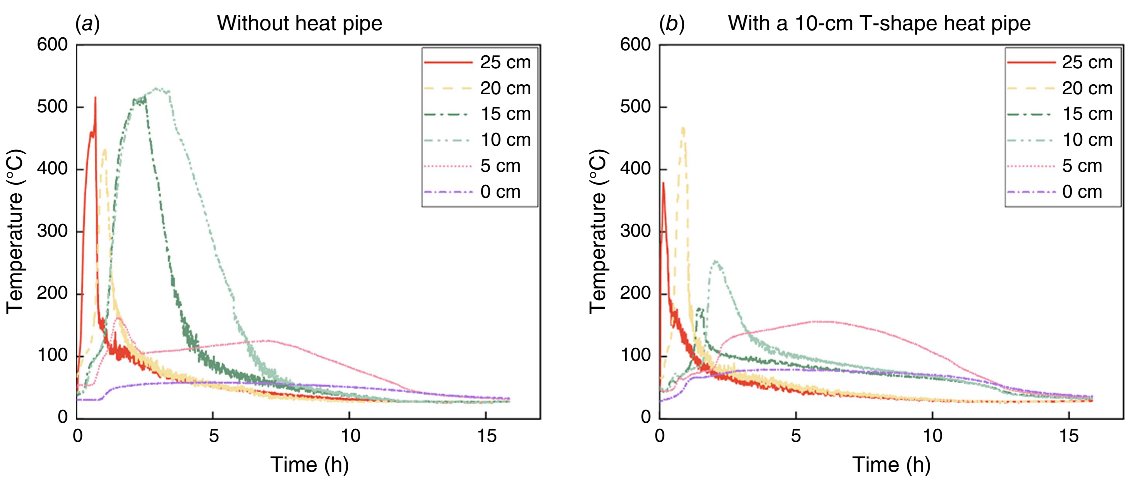

Fig. 3. Temperature evolutions of burning peat columns: (*a*) without heat pipe (baseline), and (*b*) with a 10-cm T-shape heat pipe buried in soil, where the 0 cm denotes the water table between dry and saturated peat.

However, a more comprehensive pre- and post-burn moisture-gradient analysis should be pursued in future work.

The safe zone thickness was quantified based on post-burn excavation and visual identification of the moist, unburned layer, supported by the temperature–depth profiles from the thermocouples. The location of peak moisture enrichment and the depth beyond which temperatures never exceeded the smoldering threshold were used to confirm the zone's extent. Quantitatively, the safe zone thickness in the control set-up ranged from 1.5 to 3.0 cm, depending on peat density and fire duration. To amplify this self-suppressing effect, heat pipes with varying designs were introduced while the cooler section (condenser) was integrated between the dry and saturated layers (see Figs 2*c* and 4*b*). By burying the heat pipe, the safe zone expanded significantly, and its thickness increased from 3 cm of baseline to 5–15 cm, depending on pipe geometry (see more comparisons in Figs 5–7).

Functionally, the heat pipe operated as a passive thermal moisture pump. During smoldering, heat was absorbed at the upper end and released at the lower end to vaporize water from the saturated layer; the vapor then rose and condensed within the dry peat, thereby elevating its moisture and forming a more robust fire barrier (i.e. firebreak). Additionally, the removal of heat from the smoldering front helped disrupt the thermal feedback loop essential for sustained combustion. Therefore, the expansion of the safe zone is attributed to the buried heat pipe's dual functionality as an underground firebreak:

(1) Direct cooling and quenching of the smoldering combustion zone, and

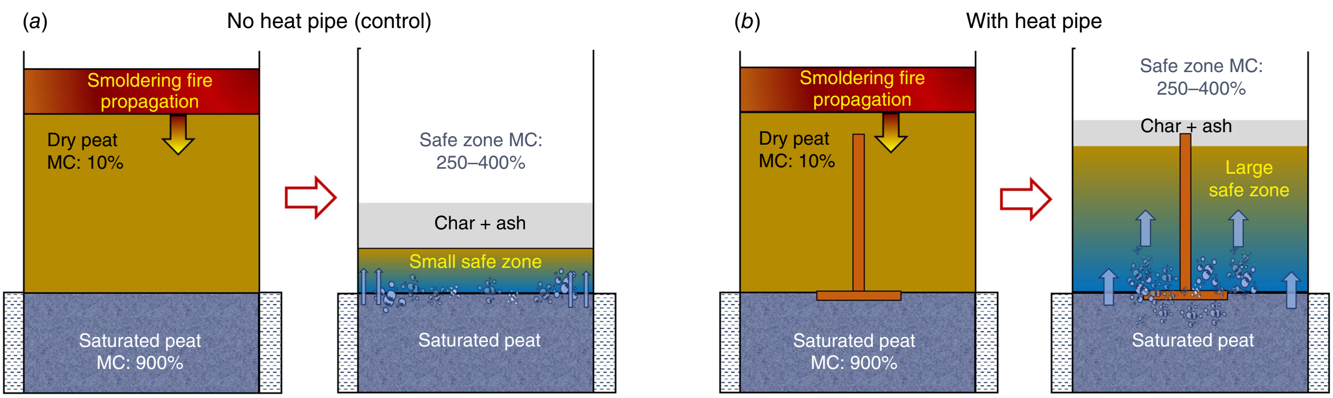

Fig. 4. Schematic diagrams of downward smoldering fire propagation: (*a*) no heat pipe as control with a small safe zone above saturated peat, and (*b*) with buried heat pipe to generate a much larger safe zone.

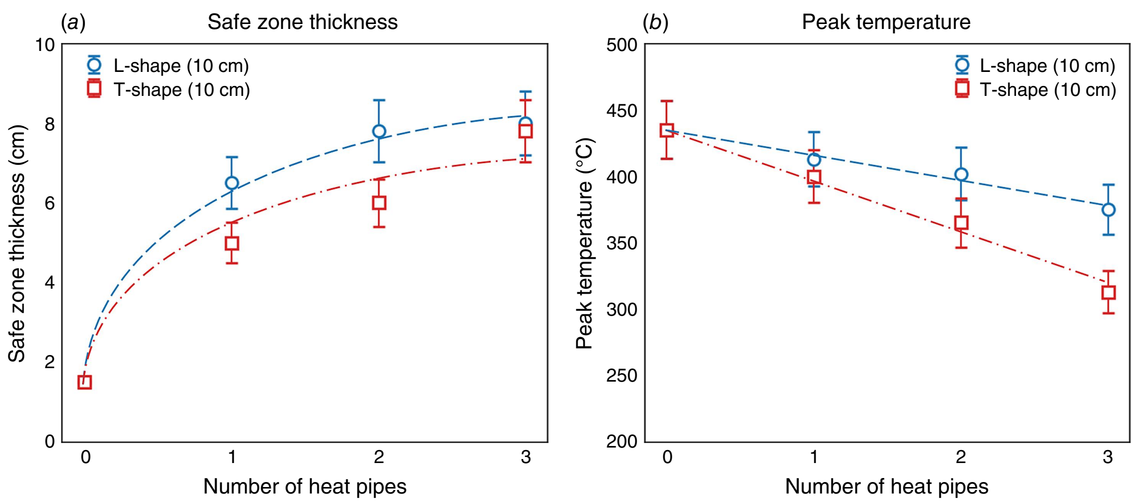

Fig. 5. Summaries of (*a*) safe zone thickness, and (*b*) peak temperature with different numbers of 10-cm L-shaped heat pipes and 10-cm T-shaped heat pipes, where the markers are average values of repeated tests and error bars are standard deviations, and the trendlines were fitted manually.

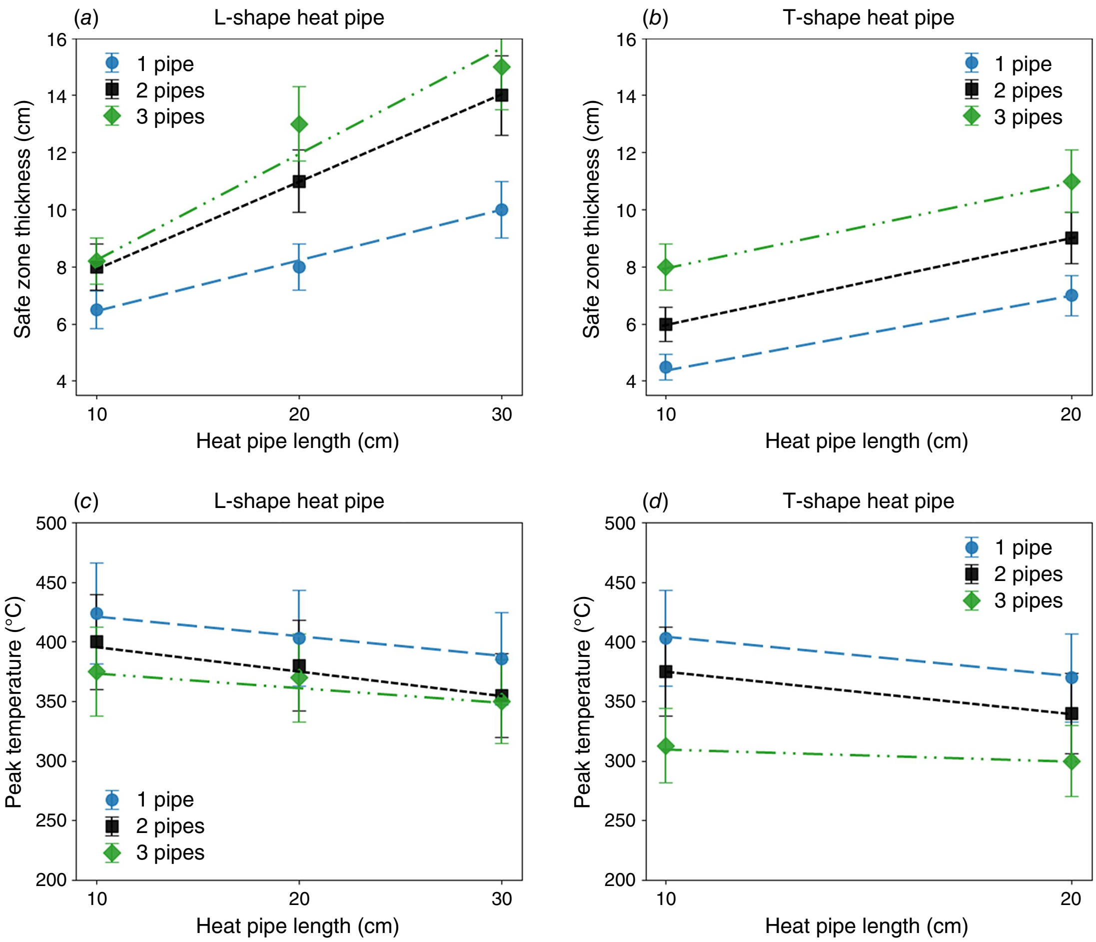

Fig. 6. Summaries of (*a*) safe zone thickness with L-shaped heat pipes, (*b*) safe zone thickness with T-shaped heat pipes, (*c*) peak temperature with L-shaped heat pipes, and (*d*) peak temperature with T-shaped heat pipes, where the markers are average values of repeated tests and error bars are standard deviations, and the trendlines were fitted manually.

(2) Promoting water evaporation from the saturated layer, which then condensed in the upper dry region to increase moisture content ahead of the smoldering fire front.

These results confirm that both natural capillary-driven moisture migration and engineered thermal control via buried heat pipes can create and strengthen protective zones within peat profiles. The synergy of these mechanisms significantly reduces the likelihood of vertical fire spread. Such findings offer valuable insights for developing passive, subsurface fire mitigation strategies in peatlands and other organic-rich soils vulnerable to smoldering ignition. Note that comprehensive volumetric characterization and scaling analysis will be an important component of future work aimed at optimizing heat-pipe density, spacing and layout under realistic peatland conditions.

Effect of heat-pipe quantity

The number of heat pipes installed in the system significantly influenced both the peak temperature within the smoldering front and the formation of the safe zone, as compared in Fig. 5 (also, see more comparisons in Fig. 7). Without heat-pipe intervention, the safe zone was thin and formed inconsistently, ranging from 1.5 to 3.0 cm in thickness. Peak temperatures in this baseline case reached ~450 ± 40°C in the dry peat zone, sufficient to initiate and sustain smoldering combustion. This confirms prior observations that peat with moisture content below 20% is highly vulnerable to self-sustaining smoldering (Lin *et al.* 2019).

The embedding of one L-shaped heat pipe (10 cm in length) reduced the peak temperature to 414 ± 40°C and expanded the safe zone to ~6.5 ± 0.6 cm. Increasing the number of pipes to two further reduced the temperature to 403 ± 39°C and extended the safe zone to ~8.0 ± 0.8 cm. The use of three pipes achieved the most pronounced effect: peak temperature dropped to 375 ± 38°C, and the safe zone reached ~8.2 ± 0.9 cm. A similar trend was observed with T-shaped pipes. These findings suggest a non-linear enhancement in thermal suppression with increased pipe number, possibly due to synergistic vapor flux overlap and more uniform spatial redistribution of heat.

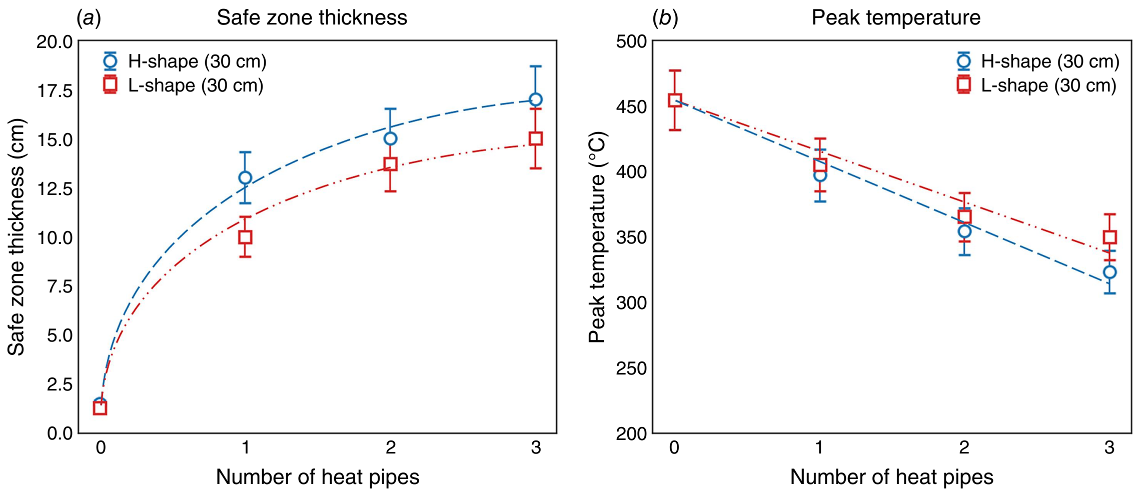

Fig. 7. Summaries of (*a*) safe zone thickness, and (*b*) peak temperature with different numbers of 30-cm L-shaped heat pipes and 30-cm H-shaped heat pipes, where the markers are average values of repeated tests and error bars are standard deviations, and the trendlines were fitted manually to show the overall trend.

Furthermore, moisture content in the safe zone increased markedly with each added pipe. In the L-shape configuration, the average post-combustion moisture content of the dry layer rose from 253 ± 30% (one pipe) to 330 ± 35% (three pipes), whereas the T-shape yielded a more dramatic increase from 332 ± 28% to 393 ± 55% across the same pipe counts. These values far exceed the critical extinction moisture content reported for tropical peat (~120–150%) (Huang and Rein 2017), suggesting that buried heat pipes not only suppress smoldering but also create self-reinforcing hydrological barriers to fire spread.

Note that the study does not determine practical pipe density (pipes per km^2) for real peatlands, which is a formal limitation, and realistic pipe spacing and density are expected to be far lower and heavily dependent on local hydrology, fuel conditions and management objectives. Determining optimal pipe spacing and density under realistic field conditions will be an important direction for future work.

Effect of heat-pipe length

The length of the buried heat pipe plays a crucial role in determining its thermal interception efficiency and subsequent enhancement of the safe zone. For example, as shown in Fig. 6*a*, experiments using L-shaped heat pipes of 10, 20 and 30 cm in length demonstrated that increasing the pipe length significantly improved thermal suppression. In the 10 cm case, with a single heat pipe applied, the safe zone formed was ~6.5 ± 0.6 cm thick and the peak smoldering temperature was 414 ± 40°C. When pipe length was increased to 20 cm, the safe zone expanded to ~8.0 ± 0.8 cm and peak temperature declined to 398 ± 37°C. The 30 cm heat pipe yielded the most substantial effect: a safe zone of ~8.5 ± 1.1 cm and a reduced peak temperature of 372 ± 40°C.

A similar trend was observed with T-shaped pipes. The safe zone expanded from ~4.5 ± 0.5 cm (10 cm pipe) to ~7.1 ± 0.8 cm (20 cm pipe), while peak temperature decreased from 403 ± 39°C to 313 ± 32°C. These results confirm that increased pipe length enhances both the depth and moisture integrity of the safe zone and reduces thermal intensity within the combustion zone under current experimental conditions.

The improved performance of longer pipes can be attributed to the proximity of their evaporator sections to the ignition front. As ignition occurred in the top layer of the dry peat, longer pipes (extending higher into the combustion zone) captured thermal energy more efficiently. This direct placement near the smoldering source accelerated the phase-change process within the heat pipe, leading to faster heat extraction, increased water evaporation from the saturated base and earlier delivery of vapor into the overlying dry zone.

Furthermore, longer pipes provided a greater thermal gradient between the hot ignition front and the cooler saturated peat, improving heat-pipe performance owing to enhanced driving potential for vapor flow and condensation. The increased moisture delivered to the dry peat layer increased its resistance to combustion, with final moisture contents ranging from 330 ± 35% (10 cm pipe) to over 400 ± 42% (30 cm pipe) using one single L-shaped heat pipe. These values far exceed the smoldering extinction threshold, confirming the functional impact of heat-pipe length on fire suppression.

Effect of heat-pipe geometry

In addition to heat-pipe length and number, the geometric configuration of the heat pipe plays a critical role in determining its thermal performance and the resulting formation of the safe zone. To evaluate this, comparative experiments were conducted using L-shaped, T-shaped and H-shaped heat-pipe designs (see Figs 6 and 7), all fabricated from copper with an outer diameter of 5 mm and tested in a vertically stratified peat column under identical ignition and moisture boundary conditions.

In general, the experiments revealed that L-shaped and H-shaped heat pipes outperformed T-shaped configurations in terms of both reducing peak combustion temperature and expanding the thickness of the safe zone. For instance, as shown in Fig. 7, with a single 30-cm pipe length and identical test set-ups, the H-shaped configuration produced a safe zone of 13.1 ± 1.5 cm, followed by the L-shaped design with 10.6 ± 1.1 cm. The corresponding peak temperatures were 386 ± 35°C and 415 ± 40°C for the H- and L-shaped pipes, respectively.

This superior performance can be attributed to the increased contact surface area between the cooled (condenser) section of the heat pipe and the saturated peat layer, which plays a vital role in sustaining evaporation and vapor transport during smoldering. The greater the surface area in the saturated zone, the more efficiently heat is extracted from the combustion zone and transferred to the cooler, moisture-rich region below. This enhances the heat pipe's ability to drive phase change, which in turn produces larger quantities of water vapor that migrate upward and condense in the dry layer, leading to moisture enrichment and suppression of smoldering reactions. In the L-shaped design, the horizontal arm lies flat within the saturated zone, ensuring a broad and stable interface for heat exchange. Similarly, the H-shaped pipe features dual vertical branches immersed in the saturated peat, effectively doubling the contact area and promoting greater heat dissipation and evaporation intensity. Measured post-burn moisture contents within the safe zone support this mechanism: the H-shaped configuration reached 432 ± 45%, the L-shaped 408 ± 41% and the T-shaped only 367 ± 39%.

In addition, the H-shape offered better vertical distribution of cooling owing to its symmetrical legs, potentially reducing lateral heat build-up near the pipe interface. Although this design is more complex to fabricate, it demonstrated the greatest balance of thermal stability and vapor redistribution under the sealed-rig conditions used in this study.

These results collectively demonstrate that heat-pipe geometry can be strategically optimized to enhance fire suppression performance in subsurface peat environments. Designs that maximize condenser surface area in the saturated zone are particularly effective and may be preferentially adopted in future field implementations.

Limitations and future directions

The laboratory experiments presented in this study provide the first evidence that buried heat pipes can function as passive subsurface firebreaks by lowering temperatures and generating moisture-enriched safe zone within peat profiles. These findings demonstrate strong potential for real-world peatland fire mitigation, particularly because heat pipes operate solely on natural thermal gradients and require no external energy input. However, the current results should not be interpreted as field-ready deployment guidelines, and meaningful translation to field application will require coordinated advances in field-scale experimentation, hydrological monitoring, material durability assessment and numerical upscaling. Therefore, several limitations inherent to the current experimental design and the complexities of natural peatland systems must be recognized when considering field translation, and these limitations simultaneously highlight the most important directions for future work.

1. A primary limitation of this study lies in its laboratory scale. The experiments were performed in a 30-cm-diameter column, where the use of one to three pipes necessarily corresponds to pipe spacings far smaller (and densities far higher) than would be plausible in natural peatlands. Within such a confined geometry, lateral heat and moisture redistribution are spatially constrained, and increasing pipe number effectively pushes the system toward intensified pipe–pipe interaction conditions that would not reflect realistic field deployment. As a result, the multi-pipe configurations should be interpreted as exploring upper-bound thermal and vapor-flux coupling under controlled conditions, rather than representing feasible field layouts. The present work deliberately focuses on mechanistic behavior rather than field-scale optimization. Practical questions regarding realistic pipe spacing, achievable density (e.g. pipes per km^2), configuration strategies, durability and logistical feasibility in heterogeneous peatland environments remain unresolved and require dedicated future investigation.
2. Another limitation concerns spatial measurement. Temperature and moisture measurements were concentrated near the heat pipes to capture the zone of strongest thermal coupling, but this approach does not fully resolve radial or axial heterogeneity within the peat. Although we report substantial moisture increases in the safe zone (rising to 400–450% compared with 250–300% in untreated peat), the lack of full three-dimensional moisture mapping limits our ability to quantify the evolution of the broader moisture field. Further experiments should incorporate denser sensor networks or advanced imaging techniques to characterize the extent and persistence of moisture redistribution across the entire column or field domain. Also, the moisture stabilization procedure introduces additional uncertainty. Equilibration over 24 h likely did not produce perfectly uniform moisture distributions, especially near boundaries, and pre-burn moisture gradients were not measured throughout the full

profile. Long-term monitoring of moisture migration before, during and after combustion would help clarify the temporal evolution of heat-pipe-driven hydrological processes.

3. Material durability represents another critical consideration. Copper was chosen for laboratory tests because of its high thermal conductivity and availability, but natural peatlands are acidic, oxygen-limited and microbiologically active environments that may promote corrosion or biofouling over long timescales. Although alternative materials such as stainless steel, titanium, or coated copper may perform better under such conditions, their long-term stability, thermal performance and maintenance requirements remain largely unknown. Field-oriented research must therefore evaluate corrosion resistance and structural longevity over multiple seasons.
4. Hydrological variability poses perhaps the greatest challenge to field deployment. The laboratory experiments assume a fixed boundary between saturated and unsaturated layers, whereas natural peatlands experience dynamic water-table fluctuations driven by seasonal cycles, drought events and drainage. Because the efficiency of the heat pipe depends on the presence of a saturated condenser zone, deep drawdown during prolonged drought or drainage may significantly reduce performance. Field application will require strategies for mapping water-table depths prior to installation, understanding performance under fluctuating hydrology and possibly designing adjustable-depth or modular systems that maintain functionality as water tables shift.

Despite these limitations, the results illustrate several compelling strengths that motivate further pursuit of this technology. A key insight from this study is the importance of protecting the upper dry peat layers, which are the most vulnerable to smoldering ignition during low-moisture periods. The heat pipe serves as both a passive thermal pump, transferring heat away from the ignition zone, and a moisture enhancement device, evaporating water from the saturated layer and condensing it in the dry zone to form a fire-resistant buffer that limits downward fire spread. Importantly, this process remains functional even under moderately lowered water tables, providing a potentially valuable complement to conventional fire management strategies such as canal blocking, rewetting, firebreak maintenance and active suppression.

The conceptual field vision builds on this synergy (Fig. 8). Heat pipes embedded in the subsurface could be paired with surface-level units cooled by natural convection, producing a vertically integrated system that stabilizes both surface and subsurface temperature and moisture conditions. Embedding thermal and gas sensors within pipe casings could enable real-time monitoring of CO, Volatile Organic Compounds (VOCs) and temperature, while wireless communication with satellite or Unmanned Aerial Vehicle (UAV) platforms would provide early detection and rapid response capability in remote regions. Such integration aligns well with emerging data-driven fire management frameworks and offers new opportunities for passive risk reduction. Furthermore, the heat pipe (upright with wind cooling) can also serve as an indicator for underground peat fires, as the exposed part of the heat pipe in the air will be hot and can be detected by an IR camera or hand-touching.

Overall, these considerations illustrate that although heat pipes show strong potential as a passive, scalable and low-

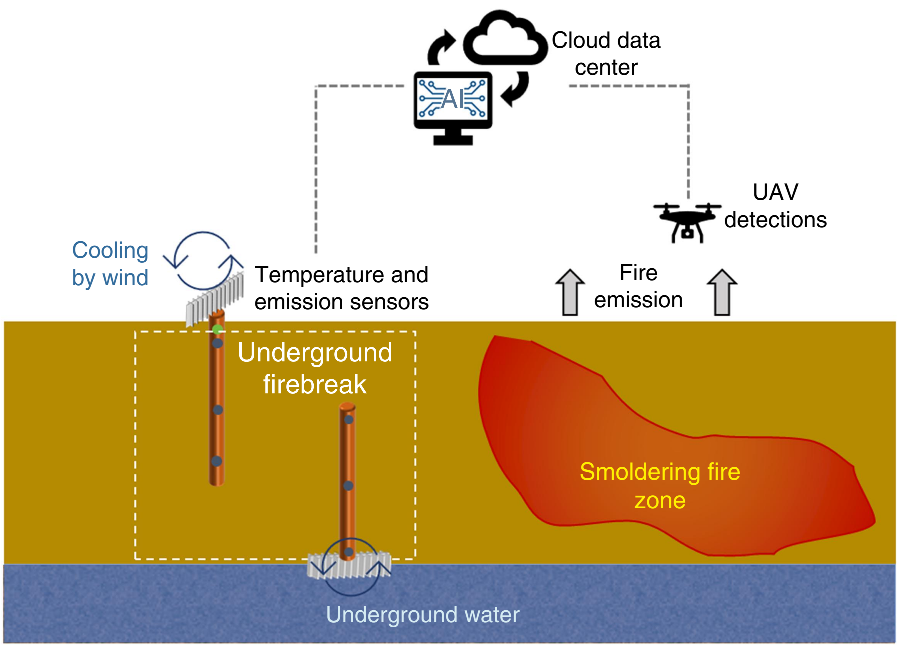

Fig. 8. Conceptual integrated system for fire detection and suppression based on water-cooling heat pipes, supported by new technologies such as unmanned aerial vehicles (UAVs) and the Artificial Internet of Things (AIoT) for monitoring and early warning.

maintenance complement to existing peat-fire mitigation practices, translating the concept from laboratory demonstration to operational management will require coordinated advances in hydrological monitoring, sensor integration, material engineering, field experimentation and ecological assessment. With further refinement and field development, heat-pipe-based systems may ultimately provide a novel pathway for reducing smoldering fire risk, preserving vulnerable peat layers and mitigating carbon emissions in threatened peatland ecosystems.

Conclusions

This proof-of-concept study demonstrates that buried heat pipes can effectively suppress smoldering peat fires by lowering subsurface temperatures and creating a high-moisture safe zone between dry and saturated layers. By passively transferring heat from the combustion front into the saturated zone, the pipes induce stronger evaporation, upward vapor migration and condensation in the dry peat, raising moisture well above the extinction threshold and greatly reducing downward fire spread. Longer pipes and geometries with larger condenser contact areas (such as the H-shape) produced the strongest cooling and moisture-enhancing effects. These findings suggest that heat pipes could serve as a valuable complement to existing peat-fire mitigation strategies and offer particular promise for remote or difficult-to-access peatlands. When integrated with hydrological management and early-warning systems, heat pipes may help protect vulnerable peat layers, limit carbon loss and support sustainable peatland management in fire-prone regions such as southeast Asia and boreal regions.

Nevertheless, several limitations remain: (1) the laboratory scale and simplified boundary conditions do not capture landscape-level variability, and pipe densities in the experiment are higher than would be used in the field; (2) material longevity in acidic, waterlogged peat and system performance under fluctuating water tables also remain uncertain; and (3) the ecological effects of localized moisture redistribution over long periods are not yet known. Future work should therefore include field-scale trials under realistic hydrological conditions, evaluation of corrosion-resistant materials, and optimization of pipe spacing and installation methods for diverse peatland settings. With further development, heat-pipe systems have the potential to become a practical and low-maintenance addition to peatland fire management and climate-mitigation efforts.

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Data availability. All raw data can be provided by the corresponding authors on request.

Conflicts of interest. Dr Xinyan Huang is an Associate Editor and Dr Shaorun Lin is a Guest Editor of the *International Journal of Wildland Fire*, but they were not involved in the peer-review or decision making process for this paper. The authors have no other conflicts of interest.

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