



A Review of Abrupt Permafrost Thaw: Definitions, Usage, and a Proposed Conceptual Framework

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Abstract

Purpose of Review We review how ‘abrupt thaw’ has been used in published studies, compare these definitions to abrupt processes in other Earth science disciplines, and provide a definitive framework for how abrupt thaw should be used in the context of permafrost science.

Recent Findings We address several aspects of permafrost systems necessary for abrupt thaw to occur and propose a framework for classifying permafrost processes as abrupt thaw in the future. Based on a literature review and our collective expertise, we propose that abrupt thaw refers to thaw processes that lead to a substantial persistent environmental change within a few decades. Abrupt thaw typically occurs in ice-rich permafrost but may be initiated in ice-poor permafrost by external factors such as hydrologic change (i.e., increased streamflow, soil moisture fluctuations, altered groundwater recharge) or wildfire.

Summary Permafrost thaw alters greenhouse gas emissions, soil and vegetation properties, and hydrologic flow, threatening infrastructure and the cultures and livelihoods of northern communities. The term ‘abrupt thaw’ has emerged in scientific discourse over the past two decades to differentiate processes that rapidly impact large depths of permafrost, such as thermokarst, from more gradual, top-down thaw processes that impact centimeters of near-surface permafrost over years to decades. However, there has been no formal definition for abrupt thaw and its use in the scientific literature has varied considerably. Our standardized definition of abrupt thaw offers a path forward to better understand drivers and patterns of abrupt thaw and its consequences for global greenhouse gas budgets, impacts to infrastructure and land-use, and Arctic policy- and decision-making.

Keywords Arctic · Boreal · Climate feedbacks · Permafrost tipping points

Main

Permafrost, or perennially frozen ground, underlies approximately 15% of land in the Northern Hemisphere [1] and regulates many characteristics of northern ecosystems including vegetation, hydrology, carbon balance, and nutrient cycling [2]. Permafrost is increasingly vulnerable to thaw, responding to rapid rates of Arctic change including warming [3], changes in precipitation and snow depth [4, 5], a longer snow-free season [6, 7], more intense wildfire regimes [8, 9], and land cover change [10–14]. Permafrost thaw occurs when previously frozen ground thaws and ground ice melts,

resulting in consequences ranging from local impacts on land stability and navigation, to regional impacts on hydrology [15] and weather [16], to broader environmental and societal consequences such as loss of soil carbon storage and release of greenhouse gasses and industrial contaminants [17–20]. Beyond broad, generalized predictions, studies are just beginning to understand how ongoing and future permafrost thaw is likely to impact ground stability and infrastructure at local to regional scales [21]. For example, one study suggests thaw could cause widespread damage to infrastructure including an estimated 120,000 buildings, 40,000 km of roads, and 9,500 km of pipelines, affecting approximately 3.6 million people by 2050 [22] and costing billions of dollars to maintain [23]. Through feedbacks to

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the global climate system, carbon emissions from thawing permafrost are expected to release anywhere from 55–232 Pg carbon dioxide equivalent to the atmosphere by 2100, amplifying anthropogenic climate change [24]. The lower end of the range reflects projections where human efforts to limit anthropogenic greenhouse gas emissions keep global warming below 2 °C, while the upper end represents projected Arctic emissions with no carbon mitigation policies.

Permafrost research generally focuses on two broad categories of permafrost thaw that have different impacts on Arctic ecosystems and the global climate [25]. First, gradual top-down thaw leads to increasing thickness of the active layer – the surface layer of vegetation, soil, and sediment that freezes and thaws annually. This type of permafrost thaw occurs relatively slowly as near-surface permafrost thaws, impacting centimeters to meters of frozen ground over years to decades [26]. Gradual, top-down thaw (hereafter referred to as ‘gradual thaw’) occurs across the entire permafrost region, and because it is ubiquitous, tends to be well-studied [27, 28]. For example, active layer thickening has been monitored for several decades at more than 200 sites as part of the Circumpolar Active Layer Monitoring (CALM) network spanning much of the Arctic permafrost region [27]. There can be subsidence of the ground surface associated with gradual thaw; however, this parameter is not as widely measured as active layer thickening and our understanding of this process is limited [29–31]. In contrast to gradual thaw, the term ‘abrupt thaw’ is increasingly used to refer to a more pronounced type of permafrost thaw largely driven by the melting of ground ice and subsequent ground surface collapse. This includes geomorphological processes such as thermal and physical erosion [32], but the definition of abrupt thaw varies between studies. Abrupt thaw is often associated with the thawing of ice-rich (i.e., > 20% ice content) [33] permafrost and is suggested to rapidly (i.e., within months to years) impact meters of permafrost both horizontally and vertically through surface subsidence and erosion. Abrupt thaw creates characteristic landforms such as thaw lakes and wetlands, retrogressive thaw slumps, active-layer detachments, and thermal erosional gullies [34–36]. Thermokarst (the process by which characteristic landforms result from the thawing of ice-rich permafrost) [26] and thermal erosion (the erosion of ice-rich permafrost by the combined thermal and mechanical action of moving water) [26] are often used synonymously with abrupt thaw, but this narrow definition excludes processes such as wildfire-induced thaw which some scientists might consider to be an abrupt thaw process. Nevertheless, the development of thermokarst landscapes is an important abrupt thaw process, and thermokarst landscapes are estimated to store approximately 330 Pg soil organic carbon within the upper 3 m, representing about 30% of the total soil carbon stored in the top 3 m of the entire permafrost region [33].

In addition to near-surface carbon, abrupt thaw often exposes deep, previously frozen carbon to decomposition and erosion, making an increasingly large soil carbon pool (~400 Pg stored in deep Yedoma and deltaic deposits) vulnerable to release to the atmosphere [37]. Despite the potential to impact only a limited area of the permafrost region (collectively ~20%) [33], empirical studies show that abrupt thaw can lead to hotspots of permafrost carbon release in these regions [38–42]. Only two out of eleven Earth system models in the Intergovernmental Panel on Climate Change’s (IPCC) 6th Assessment Report represent some form of permafrost carbon feedback to climate, and none yet include abrupt thaw processes [43]. This is because large-scale models currently lack the architecture required to simulate the complex, three-dimensional changes in hydrology, vegetation, and surface elevation changes that drive the formation and expansion of abrupt thaw. They also lack representation of the three-dimensional structure of soil carbon and ground ice distribution that governs carbon release and thaw dynamics. As a result, abrupt thaw carbon release has been assessed using independent approaches outside of Earth system model frameworks, though it is acknowledged as one of the unresolved processes within Earth system models [44]. For example, first order inventory model simulations suggest net cumulative abrupt thaw carbon emissions on the order of 80 ± 19 Pg carbon by 2300, accounting for approximately 40% of the mean net emissions attributed to gradual thaw [38]. However, in these simulations, carbon emissions from abrupt thaw are expected to have the same radiative forcing and global warming impacts as gradual thaw due to large methane emissions. Still, carbon emissions from abrupt thaw remain difficult to upscale or model due to uncertainties in the current and future spatial extent of abrupt thaw, the diversity of thaw processes involved, their variability in carbon dioxide versus methane emissions, and the duration over which these processes release significant amounts of carbon. Due to their increasing occurrence, dramatic alteration of the landscape, and potential strong feedbacks to global climate, there is a need to more thoroughly study abrupt thaw processes. This first requires adequately defining and contextualizing abrupt thaw relative to other permafrost-specific geomorphic processes and general landforming and geological processes in the Earth system. In this paper, we review the varied historical use of the term abrupt thaw and build a framework for how it should be used consistently in the future.

‘Abrupt Thaw’ in the Literature

We conducted a literature search of peer-reviewed studies in journal articles, reports, and textbooks to explore the origin and evolution of the term ‘abrupt permafrost

thaw' (Supplementary Table 1). We used Web of Science and Google Scholar to identify studies that mention 'abrupt thaw' in the context of permafrost and either explicitly or implicitly define the term. Our search terms resulted in a review of 226 studies. Abrupt thaw was often used to describe thermokarst, thaw slumps, thermal erosional processes, or a rapid rate of thaw (days to years). However, definitions of abrupt thaw varied considerably among articles and were broad in scope. We found the usage of abrupt thaw can be grouped into three categories: formation of thermokarst and thermal erosion features, a rapid rate of thaw, or a combination of both thermokarst development and a rapid rate of thaw (Fig. 1).

Jorgenson et al. [32] initially described an abrupt increase in ice-rich permafrost degradation, resulting in thermokarst depression formation beyond normal rates of landscape change. The authors never specifically mentioned 'abrupt thaw' and instead used abrupt to describe a rapid change in permafrost conditions. Schuur et al. [45] also described abrupt thaw processes, stating, "Although permafrost thawing can occur gradually as the thickness of the active layer increases, it can also occur more abruptly through development of thermokarst (ground surface subsidence caused by thaw of ice-rich permafrost) and erosion." The first use of 'abrupt thaw' was by Schuur & Abbott [46] who defined it as processes that "can cause ice wedges to melt and the ground surface to collapse, accelerating the thaw of frozen ground." Most papers over the next few years continued to use abrupt thaw as synonymous with thermokarst or thermal erosion or a rate of thaw. Grosse et al. [36] described how rapid (pulse) disturbances are more associated with abruptly thawing permafrost and can be triggered by gradual (press) disturbances such as top-down permafrost thaw. Schneider von Deimling et al. [47] defined abrupt thaw as "thaw on

a decadal scale" and included processes such as wildfire-induced thaw and coastal erosion. This was the first study to include processes other than thermokarst within the scope of abrupt thaw. They also noted that abrupt thaw must occur on sub-decadal time scales, using rate of thaw as the defining characteristic.

In 2016 and subsequent years, the use of abrupt thaw in the literature diversified, often defining abrupt thaw as a process that is both rapid and causes a pronounced physical change on the landscape without specifying the features that fall within those categories (Supplementary Table 1). Around the same time, a strong emphasis on ice-rich permafrost degradation emerged, stating that permafrost must be ice-rich for abrupt thaw to occur. The argument is that when ground ice melts, it causes the land surface to subside and amplifies rates of permafrost thaw through self-reinforcing feedbacks. Turetsky et al. [38] defined abrupt thaw as processes such as thermokarst that can affect meters of permafrost soil in periods of days to years [38]. This study was unique in its definition because it referenced the amount of thaw (in meters of impacted ground) within a given time frame for thaw processes to be considered abrupt.

Abrupt thaw is a useful term for communicating a broad range of geomorphological processes in a generalized, simple framework. However, our literature review reveals that abrupt thaw is used inconsistently. Definitions range from using the term synonymously with thermokarst to broadly encompassing a wide variety of processes (wildfire-induced thaw, coastal erosion, thermal erosion, ecosystem collapse) and timescales (days, weeks, months, years, decades). Most studies do not explicitly define abrupt thaw but instead give examples of a type of abrupt thaw such as thermokarst formation or thermal erosion, leaving room for other processes to be included in this definition without explicitly naming them.

Fig. 1 A plot of the cumulative number of publications per year using the term 'abrupt thaw' to describe either the occurrence of thermokarst/thermal erosion, a rapid temporal rate of thaw, or a mix of these categories

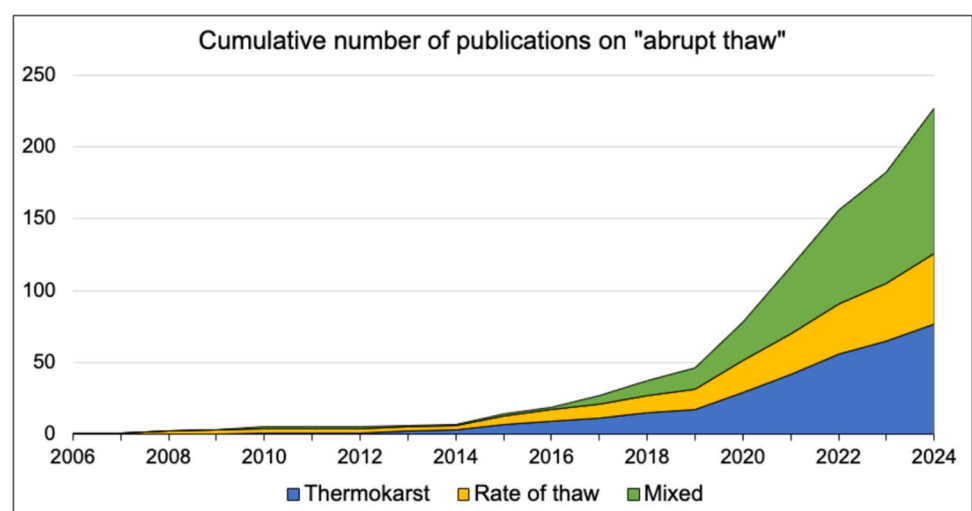


Table 1 Conceptual box defining terms related to abrupt change in the Earth Sciences

Beyond permafrost - themes underpinning abrupt change in the Earth Sciences

Disturbance: An event that causes temporary and localized shifts in the physical structure or arrangement of biotic and abiotic elements of an ecosystem

State change: An abrupt shift leading to differing arrangements of an ecosystem's characteristics, such as its functions, processes, components, and interrelationships

Threshold: Point at which a persistent change in an ecosystem quality, property, or phenomenon occurs

Tipping point: A type of threshold in which, once reached, the system rapidly changes its state

'Abrupt Change' in Other Disciplines

It may be illuminating to frame abrupt thaw beyond the foundational fields, processes, and scales that define permafrost systems and their importance to society and climate. Here we draw on other disciplines and their definitions of abrupt change to identify key concepts that we think are useful to our goal of reaching a standardized definition of abrupt permafrost thaw.

Abrupt ecological change is defined as substantial changes in ecosystem states that occur in short periods of time relative to typical rates of change in the system or are rapid relative to their drivers [48]. **Disturbances**, such as wildfire or permafrost thaw, may impact ecosystems through changes in frequency or return interval, size, intensity, and severity of change [36, 49–55] (see Table 1). Abrupt ecological change is often used to describe disturbances that result in ecosystem **state changes** and may or may not be associated with **thresholds** or **tipping points** (see Table 1). Finally, abrupt ecological changes often result from interacting drivers. For example, in the context of permafrost systems, climate warming interacting with severe burning can trigger abrupt permafrost thaw.

Within the climate and geoscience fields, abrupt change has been defined by a rate of change ("a large change within less than 30 years" [56] and "a transition in the climate system whose duration is fast relative to the duration of the preceding or subsequent state" [57]). Thirty years is a relevant time frame because changes that occur in less than 30 years may have too much noise (i.e., influences of short-term fluctuations like weather and temporary ecosystem disturbances) while change occurring over a 30+ year period may not be relevant for effective policy making. Abrupt change has also been defined as a rapid initiation of a state change ("when the climate system is forced to cross some threshold, triggering a transition to a

new state at a rate determined by the climate system itself and faster than the cause" [58]); a change involving a tipping point (abrupt changes that pass a critical threshold, or tipping point, after which cascading impacts on ecosystems may follow [59]); and the severity or magnitude of change (abrupt change has been defined by the magnitude of impact regardless of whether those changes occurred on time scales of centuries or 10,000+ years [60]).

In their review of abrupt climate and ecological change, Botta et al. [61] proposed that definitions of abrupt change should consider the frequency/timing, severity/magnitude, as well as the persistence of change. They propose the following definitions:

Gradual change—change provoked by direct linear forcing.

Rapid change—a large-scale change in the climate system that takes place over a few decades or less, persists (or is anticipated to persist) for at least a few decades and causes substantial disruptions in human and natural systems.

Abrupt change—change that causes a system to cross a tipping point and switch to a new state.

These frameworks are helpful for merging key concepts found across the ecological, climate, and geological disciplines reviewed here. We apply these concepts to the permafrost system to articulate a definition of abrupt thaw that can be utilized in a more consistent way across permafrost studies. We conclude that a definition of abrupt thaw should include: (1) thaw that occurs more rapidly than typical permafrost degradation (i.e., gradual top-down thaw), and (2) thaw that leads to substantial alteration of the structure, integrity/stability, or function of permafrost systems that persists longer than those caused by gradual thaw.

Key Questions to Consider when Seeking a Definition of Abrupt Permafrost Thaw

We developed conceptual diagrams to visualize the formation time, degree/magnitude of ecosystem change, average feature size, and scale of impacts for common permafrost thaw processes (Fig. 2 and 3). We used mean literature values from 44 studies and our expert assessment to place a variety of permafrost thaw processes into these two-dimensional spaces (Supplementary Table 3). In some cases, disturbances such as wildfire or human activity (i.e., seismic lines or other linear features [62, 63]) remove the surface organic layers that insulate permafrost and amplify both thaw rates and ecosystem change. Here we consider the cumulative impacts of these changes as there is insufficient information to examine processes individually. We acknowledge that across all types of permafrost thaw processes, the rate of permafrost change and the magnitude of ecosystem impacts vary widely in relation to ice content, vegetation type, and other key driving factors. We use the information from Fig. 2 and 3 to explore several conditions of the permafrost system and ask how they are related to the potential for abrupt thaw.

How Rapidly Does Permafrost need to Thaw for it to be Considered Abrupt?

Thaw processes can be classified as abrupt thaw when they occur rapidly (less than 30 years) and cause large ecosystem changes or complete state change. Conversely, processes cannot be considered abrupt thaw when they occur on the same time scales as gradual top-down thaw (30+ years to centuries) and have low to moderate ecosystem impacts. Abrupt thaw processes must be initiated within that 30-year time interval, however, it may take more than 30 years for a feature to fully develop. Using thermokarst lake formation as an example, melting ice wedges may cause meters of ground subsidence over the course of a decade, but the lake can continue to deepen and expand gradually over the course of a century. This is still considered abrupt thaw because of the rapid initiation of the feature. The ambiguity lies with thaw processes that occur rapidly but do not have large ecosystem impacts. For example, talik formation (perennially thawed regions of ground found in a permafrost environment) [64] can happen rapidly but this individual process may not cause significant changes to the ecosystem. The primary

Time Scales and Ecosystem Impacts of Permafrost Thaw Processes

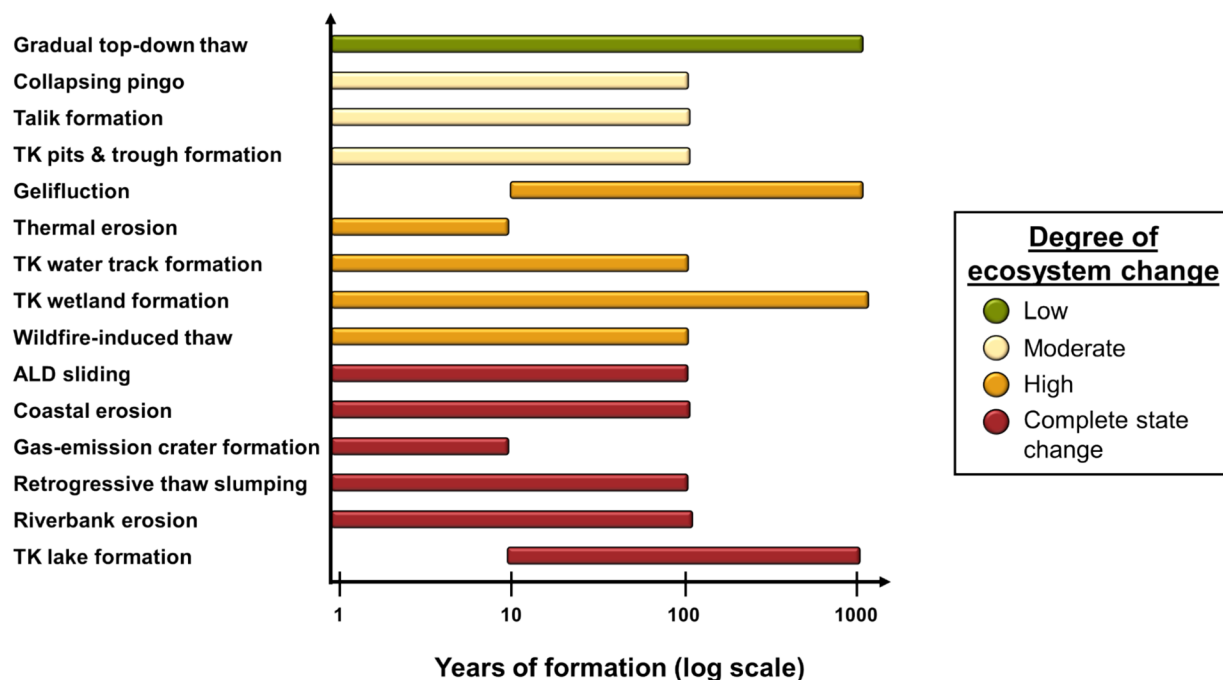
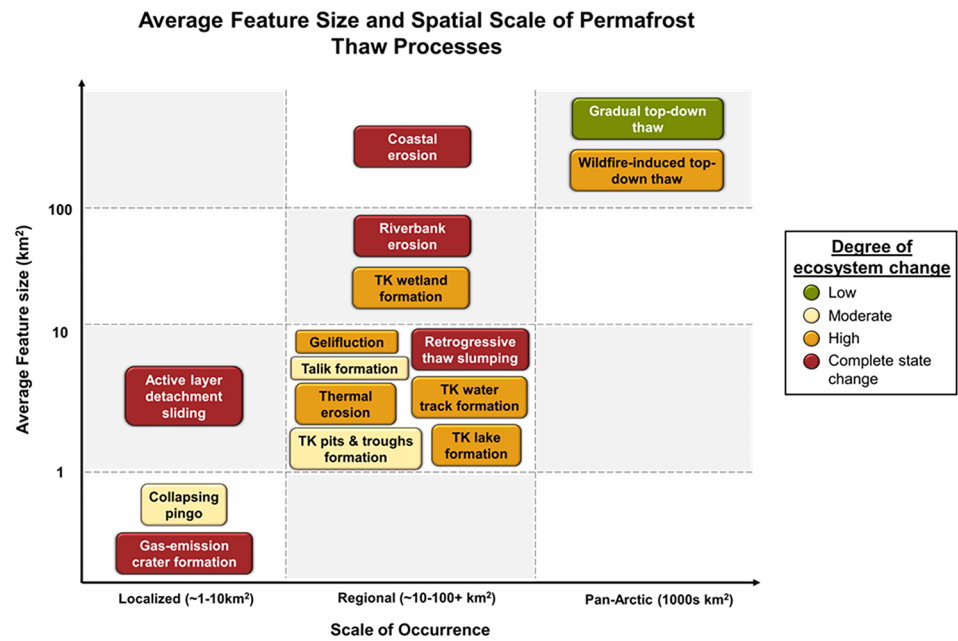


Fig. 2 Permafrost thaw processes at the landform scale showing the time it takes for each process to form and the degree of ecosystem change. Definitions of the degree of ecosystem change categories

were adapted from Turner et al. (2020) [48] and are detailed in Supplementary Table 2. Abbreviations: Thermokarst (TK) and Active layer detachment (ALD)

Fig. 3 The average feature size and scale of occurrence for permafrost thaw processes. The scale of occurrence reflects the maximum extent of the permafrost region likely to be affected by each process. Feature sizes are based on average estimates and individual instances may occur outside the ranges shown. The degree of ecosystem change is represented by the color of each word bubble. Abbreviations: Thermokarst (TK)



distinction between rapid and abrupt thaw is that rapid thaw refers solely to the rate of permafrost thaw, whereas abrupt thaw also entails substantial and persistent changes to ecosystem structure or function. For instance, wildfires typically lead to rapid permafrost thaw due to combustion of the insulating organic soil layer and albedo reductions [65]. However, wildfire-induced permafrost thaw can only be classified as abrupt if it is accompanied by ground subsidence, altered local hydrology, or some other change to ecosystem identity and function. We conclude that the definition of abrupt thaw should not be based solely on the rate of thaw-induced change but should also include the processes causing long-lasting and substantial impacts to the ecosystem.

Does Abrupt Thaw Always Occur in Ice-Rich Permafrost?

Ground ice is a key factor contributing to abrupt thaw processes, but not required. Ground ice originates from rain, spring snowmelt, buried glacial ice, snow patches, or fresh-water pond ice. However, ground ice is extremely heterogeneous over many scales and may range from pore ice, a barely visible cement holding silt and sand grains together, to centimeters-thick segregation ice common at the base of the active layer, to large massive ice bodies formed by different processes in the past. Massive ice wedges can be tens of meters tall and the ubiquitous presence of readily visible “patterned ground” indicates their presence over much of the permafrost domain [66]. Buried glacial ice consists of sometimes tens of meters thick ice beds extending over kilometers in regions that were formerly glaciated [67].

The presence and colocation of these ice features, their bulk density, and their formation histories are difficult to quantify at large scales. Regardless of its formation history, the melting of excess ground ice (massive ice bodies or segregated ice exceeding the normal pore space volume of a sediment) causes rapid geomorphologic changes. The phase change from ice to water decreases volume by 9%, creating voids and channels in the surface. Surface subsidence leads to changes in surface elevation at a variety of scales. The degree of soil or sediment subsidence post-thaw is directly correlated to the ground ice content of permafrost. In many instances, once surface subsidence has initiated, multiple positive feedback mechanisms may result in an acceleration of thaw and subsidence, eventually resulting in abrupt landform change. These positive feedbacks increase heat influx into the ground, including water pooling and snow accumulation in subsided areas and enhanced erosion. In contrast, permafrost with extensive ground ice can experience longer thaw duration due to the greater amount of energy necessary for the phase change from ice to liquid water.

While the peer-reviewed literature often defines abrupt thaw as only occurring in ice-rich permafrost, we identified a number of processes that occur rapidly with significant ecosystem impacts that do not necessarily occur only in ice-rich permafrost, such as wildfire-induced top-down thaw, riverbank erosion, and coastal erosion (Fig. 2). From this, we conclude that while ground ice is an important factor contributing to abrupt thaw in some areas, abrupt thaw does not occur solely in ice-rich permafrost and thus the definition of abrupt thaw should not be based on the presence of ground ice.

How do Thaw Mechanisms, the Scale of Occurrence, and Ecological Impact Vary for Abrupt Thaw Processes?

Multiple thaw processes can occur in an ecosystem at the same time, and some processes can trigger or amplify others. For example, talik formation can eventually lead to the formation of thermokarst features or vice versa [68, 69]. Additionally, rapid active layer thickening caused by severe wildfire can trigger active layer detachment slides in sloped areas. Many of these thaw processes are linked and the dominant force of thaw in these systems may change over time with shifts in ecosystem function and identity. None of this complexity is captured in large-scale models, as most modeling frameworks lack the capability to represent any form of abrupt thaw.

Some thaw processes are more common and impact larger portions of the permafrost region while others are less frequent or extensive. For example, in boreal peatlands and lowlands, wetland thermokarst features can occupy > 60% of the landscape [33], causing significant disruption to local infrastructure and ecosystems and releasing substantial amounts of greenhouse gases, particularly methane [39, 40]. On the other hand, gas-emission craters are a very dramatic and extreme version of abrupt change in permafrost systems. They are formed by an explosion that leaves behind a massive crater measuring dozens of meters wide and deep [70]. There is uncertainty about whether the craters are formed as a result of temperature or hydrologically-driven permafrost thaw or mechanical permafrost degradation from below-ground gas buildup and pressure [71, 72]. Although these events receive lots of media attention due to their impressive size and rapid appearance on the landscape [73–75], these craters are isolated and have only been observed in the northern part of the West-Siberian Plain on or near the Yamal Peninsula [70, 76]. Even though the impact of gas-emission craters on the local terrain is substantial, their socioecological consequences on ecosystem- to climate-system scales are more limited. As such, the diversity of abrupt thaw types and both scope and scale of their consequences may necessitate different abrupt thaw classification schemes for various purposes. Local infrastructure planning for example may need to place priority on understanding different abrupt thaw features and their impact on local terrain land use change.

How do Abrupt Thaw Processes Differ in their Contribution to the Permafrost Carbon Feedback?

Thaw processes can vary in their contribution to greenhouse gas emissions, depending on the volume of thaw-affected permafrost as well as the biogeochemical and hydrological setting resulting from thaw. In general, lowland thaw features

tend to be wetter and emit more methane than upland thaw features [38]. Within lowland thaw areas, thermokarst lakes can vary depending on their surrounding permafrost characteristics and as a result can be high or low emitting sources for biogenic methane [77]. Some lakes develop deep taliks that facilitate tapping into deeper geologic gas sources, allowing natural gas seepage from sedimentary basins to occur [78]. Thus, some thermokarst lakes emit significantly more methane than others, highlighting the variability in greenhouse gas emissions within a single type of abrupt thaw feature. This variability within features can substantially affect their contribution to the permafrost carbon feedback and broader climate change. Accounting for this variation requires knowledge not only of abrupt thaw features but also the role of biogeochemical cycling, permafrost history, geological substrates, hydrology, and vegetation in regulating greenhouse gas emissions and lateral carbon release [79, 80]. The current and potential emissions associated with each abrupt thaw process shown in Fig. 2 remain largely unknown, but some estimates have been made based on limited data from collapse-scar wetlands, thermokarst lakes, and hillside erosion [38, 81–84]. While regional to pan-Arctic scale processes are expected to have a greater impact on carbon emissions than localized processes, there is a lack of supporting data. Improving our understanding of these emissions should be a priority for future research.

Abrupt thaw landforms also vary in their trajectory of recovery following permafrost thaw, including the rate of ecosystem stabilization and possible reformation of permafrost. Thermokarst may trigger large carbon releases in the short-term but eventually transition to an ecosystem state that accumulates soil carbon, often facilitated by lake drainage and fen/bog vegetation expansion [85–87]. Wild-fire can increase ground thermal conductivity and reduce surface albedo causing rapid active layer thickening [88] and long-term permafrost thaw. Some permafrost is resilient to this type of disturbance and can stabilize and even re-aggrade within several decades [65, 89]. While gradual thaw mostly causes linear changes to permafrost systems over time, the long-term impacts of abrupt thaw are difficult to predict because of complex successional trajectories. In landforms undergoing abrupt thaw, the forcing (typically rising air and/or soil temperatures) often triggers nonlinear effects on the rate of permafrost thaw. A prime example of this is ice-rich permafrost thaw leading to thermokarst formation. Gradually rising air temperatures thaw the upper layers of permafrost by a few centimeters each year, but when the thaw front reaches ice, liquid water can trigger rapid thaw causing meters of subsidence in one season or year in its most actively thawing stage. Once most of the ice has finished melting, thaw rates will often decrease and stabilize as the thermokarst feature begins to enter a new steady state. However, changes in vegetation caused

by wetting and subsidence can create positive feedbacks to additional surface warming that can accelerate the rate of thermokarst development [90]. Such non-linear responses differentiate abrupt from gradual permafrost thaw processes but also highlight the difficulties of simulating abrupt thaw in Earth system models.

Modeling Abrupt Thaw

Modeling abrupt thaw is particularly challenging due to several limitations. Because of the high computational demands of simulating fine-scale landscape heterogeneity, most land components of Earth system models (ESMs) operate at coarse resolutions (i.e., ≥ 1 km) which are too large to identify small-scale phenomena such as individual thermokarst features that occur over meters to 10s of meters. Incorporating abrupt thaw into models is further complicated by a limited understanding of: current abrupt thaw feature distribution and rate of growth/stabilization; where, when, and how quickly future abrupt thaw features will form at the pan-Arctic scale; greenhouse gas emissions from abrupt thaw features (due to a lack of data and potential research bias towards high-emitting abrupt thaw features); and the substantial variability in emissions even within the same feature type. It is particularly difficult to simulate the dynamic interactions between the ground surface, water table, and frost table that cause shifts in ground subsidence and hydrology during abrupt thaw processes, though fine-scale efforts are underway [91]. These surfaces shift in complex, three-dimensional patterns which differ from the more one-dimensional increase in active layer thickness typically associated with gradual thaw. Wildfire-induced abrupt thaw may be more tractable than thermokarst or other fine-scale processes due to the larger spatial scale of wildfire and efforts to resolve heterogeneity in wildfire and other disturbance processes in models. These disturbances, often driven by the redistribution of water linked to geomorphological changes, not only affect the immediate area but also impact the broader landscape, further complicating large-scale assessments of abrupt thaw's impacts. Another limitation is the lack of fine-scale ground ice maps. Ground ice plays a crucial role in driving many abrupt thaw processes, but mapping its extent at fine spatial scales remains a challenge because it is a subsurface feature that cannot be directly observed using satellite imagery. However, there have been attempts to map small scale abrupt thaw permafrost features with high-resolution satellite imagery [92–95].

Long-term hydrologic uncertainty adds another layer of complexity: it remains unclear if and when thermokarst lakes

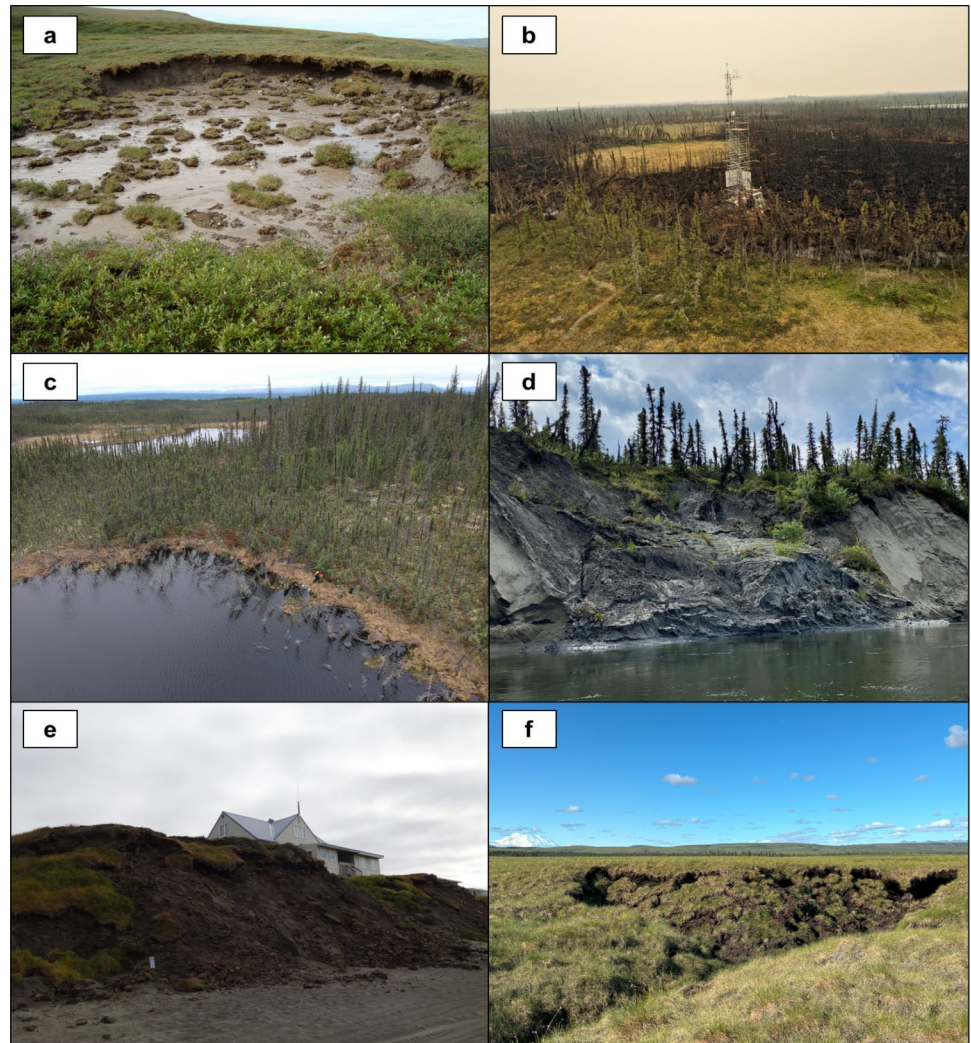
will drain, resulting in major implications for greenhouse gas emissions [40]. Methane is more likely to be produced under wet conditions, resulting in more potent short-term greenhouse gas effects, while drier conditions are associated with more carbon dioxide release [37, 96]. Finally, the age and formation history of abrupt thaw features may influence their emissions [97]. Some present-day thermokarst lakes are thought to have repeatedly formed and drained since the end of the Pleistocene [98], suggesting their soil carbon has already undergone some level of microbial decomposition one or more times [99]. In contrast, newly formed thermokarst lakes may expose previously frozen, carbon-rich soils for the first time, potentially leading to higher emissions. These uncertainties highlight the need for a better understanding of how to define abrupt thaw so that we can prioritize more research into this type of thaw and improve emissions projections from permafrost soils.

New approaches using artificial intelligence (AI) offer a promising path for improving abrupt thaw feature mapping and modeling, starting with targeted pilot studies that leverage data-driven methods to capture fine-scale thaw dynamics from multi-source data (i.e., ground observations and drone or satellite imagery) with greater computational efficiency [100, 101]. These models can uncover emergent patterns and relationships that are difficult to represent using traditional physics-based approaches alone. Insights gained from such studies can then inform and refine our physical understanding of thaw processes. By integrating this knowledge into ESMs – either through hybrid modeling or by constraining AI models with known physical processes – we can improve the representation of abrupt thaw in large-scale climate simulations.

A Framework for Classifying Abrupt Thaw

Our literature review and analyses considered three defining characteristics of permafrost thaw processes: 1) the mean rates of thaw, 2) the degree of ecosystem change, and 3) whether or not the process requires high ground ice content. We conclude that abrupt permafrost thaw includes processes by which permafrost thaws within a season to a few decades and causes substantial and sustained geomorphological, hydrogeological, or ecological changes to the system, specifically at the landform scale (Fig. 4). This process can happen in ice-rich permafrost where internal feedbacks from melting ground ice or subsidence-driven changes in vegetation accelerate thaw. However, abrupt thaw can also occur when an external factor such as wildfire, changing hydrology, or gas buildup causes permafrost to thaw or deform faster than it would by air or soil temperature changes alone. This can

Fig. 4 Photographs of common abrupt thaw landforms: **a)** retrogressive thaw slump near Toolik Field Station, Alaska, USA; **b)** wildfire-induced thaw at Scotty Creek Landscape, a flux tower of the AmeriFlux network (AmeriFlux ID: CA-SCC) near Fort Simpson, NT, Canada; **c)** thermokarst lake near Wrigley, NT, Canada; **d)** riverbank erosion along the Gulkana River, Alaska, USA; **e)** coastal erosion near Utqiagvik, Alaska, USA; **f)** thermal erosion gully in Denali National Park, Alaska, USA



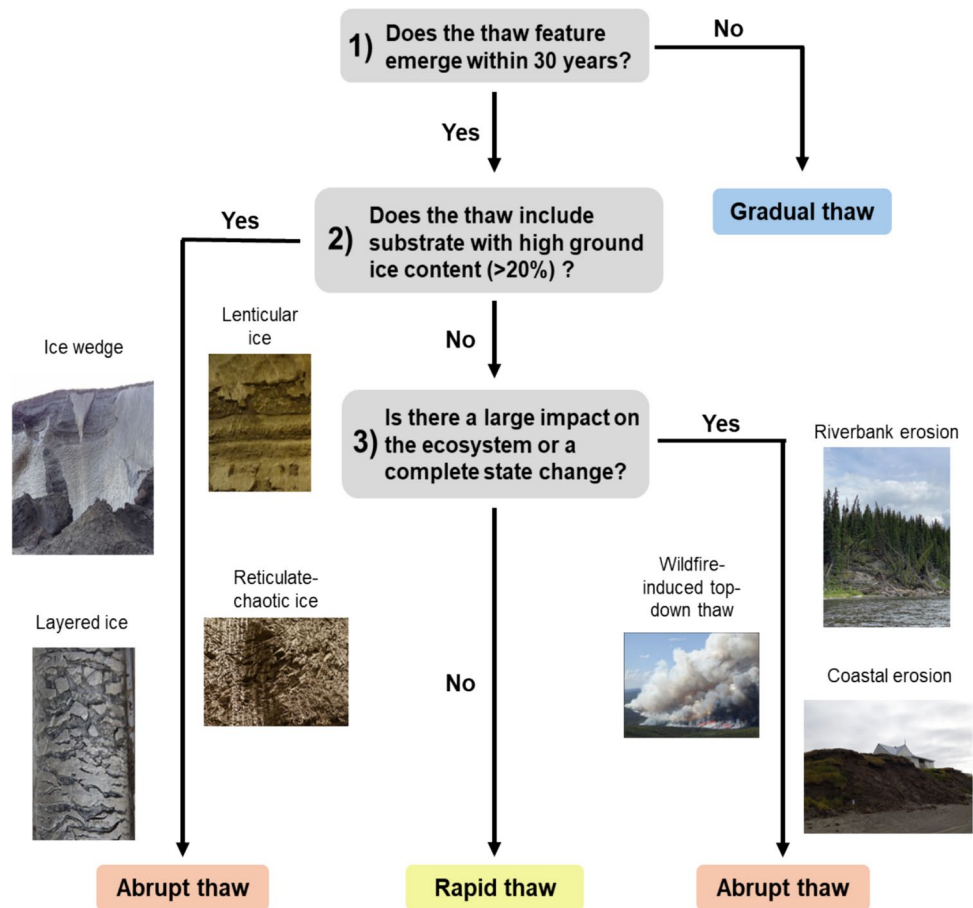
occur in systems underlain both by ice-rich and ice-poor permafrost. Using this definition at the landform scale, we outline a simple decision tree to determine whether or not a thaw process or feature should be classified as abrupt thaw (Fig. 5).

In landforms with high (> 20%) ground ice content, thaw typically will be abrupt due to hydrologic change and significant volume loss. In some instances, abrupt thaw can be preceded by many years of gradual thaw processes until the thaw front reaches the ice-rich substrate. Abrupt thaw in ice-poor landforms requires an external factor to the system instigating thaw beyond the typical rates of permafrost thaw occurring with rising air or soil temperatures alone. Examples include: rapid top-down thaw caused by an extreme wildfire resulting in active layer deepening at rates much faster than would have been expected without the influence of fire; rapid coastal erosion caused by rising sea levels; and riverbank erosion caused by increased glacial runoff and higher water levels.

Continued Use of the Term “abrupt thaw”

We show that abrupt thaw has been embedded in the literature for over a decade. Abrupt thaw was initially used to describe rapid permafrost thaw and over time developed into a multi-faceted term to describe complex geomorphological and environmental conditions that may cause permafrost to thaw faster than anticipated by an increase in air or soil temperature alone. Definitions vary across publications and the term is used inconsistently. Nevertheless, the concept of ‘abrupt thaw’ is helpful for categorizing thaw processes distinct from gradual top-down thaw. This concept also encapsulates the extensive, technical permafrost terminology in a way that will be more easily understood by the public, media, and may also offer insight into how these permafrost processes may be generalized for inclusion in large scale models [38]. Discontinuing the use of the term abrupt thaw would be a disservice due to its widespread use in the literature and its educational power in science communication

Fig. 5 Decision tree outlining the method of classification for abrupt, rapid, and gradual thaw processes/features at the landform scale. Note that this decision tree refers to permafrost thaw and not physical degradation of permafrost such as mining, drilling, or infrastructure development



efforts. However, abrupt thaw should not be used as synonymous with thermokarst/thermal erosion. In most cases, using a more specific reference to thermokarst or thermal erosion is more appropriate and lessens ambiguity because precise definitions of these terms have already been resolved. These specific terms are beneficial when discussing geomorphologic processes and the development of particular landforms. We suggest that abrupt thaw should be used when communicating to generalized audiences, describing multiple types of abrupt thaw processes, or dealing with general concepts of abrupt permafrost change.

We recommend that continued use of the term ‘abrupt thaw’ follow the classification outlined in Fig. 5. Adopting this formalized method for abrupt thaw classification will lessen ambiguity surrounding the term and improve future research on the causes and consequences of this broad suite of permafrost changes. Most efforts to model greenhouse gas contributions to the climate system from thawing permafrost have only considered gradual top-down thaw [43]. However, several studies focusing specifically on abrupt thaw have demonstrated that these processes serve as hot-spots for greenhouse gas emissions [38–41, 102, 103], and that we will underestimate the permafrost carbon feedback

to climate without considering carbon emissions from abrupt thaw features.

Beyond climate feedbacks, abrupt thaw is destabilizing soils and coastlines, forming areas of flooding and inundation in some regions and leading to catastrophic erosion and lake drainage in others. Because abrupt thaw invokes significant changes to landscapes and the ecosystem services that many northern Indigenous and non-Indigenous communities rely upon, it is imperative to incorporate abrupt thaw into current and future land planning and management schemes across the Arctic. Our study provides clarity about what constitutes abrupt thaw and how this term should be used consistently in the future, which we believe will be imperative for both scientific research as well as meaningful policy related to Arctic change.

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Author Contribution H.W., M.F., M.R.T., M.C.J., T.A.D., G.G., E.A.G.S., and J.S. were the initial core group of authors who started to conceptualize the review paper on abrupt thaw and were involved in idea development and design. We brought this paper idea to the Permafrost Carbon Network meeting in Flagstaff, Arizona and ran a workshop on abrupt thaw. Due to the massive interest in this topic and the necessity for agreement on unified terminology, we added the remaining coauthors to bring together a wide variety of permafrost scientists. During the writing process, each coauthor was assigned a unique permafrost thaw process and asked to conduct a literature review to determine the average formation time and ecosystem impacts of their chosen thaw process. Here are the coauthors and their assigned thaw process(es): G.G.—coastal erosion, thermokarst pits & trough formation, and riverbank erosion, J.G.E.—palsa, A.V.—pingo, E.S.E.—gas emission crater formation, S.M.N.—Gelifluction, E.A.G.S. & W.L. & M.F.—retrogressive thaw slumping, H.K.—talik formation, E.L.—thermo-erosion, C.S. & T.A.D.—thermokarst lake formation, M.M.L.—thermokarst water track formation, M.C.J. & O.S. & D.O.—thermokarst wetland formation, and M.G.—top-down or lateral thawing. The information gathered from each coauthor's literature review was consolidated into Fig. 2. M.C.J., G.G., and M.R.T. wrote the section titled "Abrupt change in other disciplines". O.S., B.W.A., E.S.E., and D.O. contributed an image to Fig. 3. H.W. conducted the literature review of abrupt thaw and designed all the figures. H.W. wrote the main manuscript text. All coauthors reviewed several drafts of the manuscript before submission and offered comments. All authors reviewed and approved of the final draft of the manuscript.

Data Availability No datasets were generated or analysed during the current study.

Declarations

Competing interests The authors declare no competing interests.

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