Permafrost degradation as a heterogeneous mosaic of tipping and non-tipping behaviour

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Abstract

Permafrost thaw can occur as widespread gradual thaw, or as abrupt thaw. Abrupt thaw can occur on decadal or shorter timescales and produce large, often irreversible changes to landscapes, ecosystems, and infrastructure. These changes are frequently described as tipping points, yet the underlying mechanisms differ substantially in their feedback structure, reversibility, and capacity for self-sustained propagation. Existing discussions therefore often conflate fundamentally different modes of permafrost degradation. Here we propose a four-class framework that distinguishes gradual, reversible non-linear, threshold, and tipping-system behaviour based on realised system dynamics. The framework classifies process behaviour within its environmental context, recognising that the same physical mechanism may occupy different classes of behaviour under different combinations of ice content, thermal margin, structural integrity, and propagation potential. We apply the framework to the principal mechanisms of permafrost thaw, assess which processes satisfy strict tipping-element system criteria, and identify the state variables governing class membership. We argue that permafrost instability is best understood as a heterogeneous mosaic of locally conditioned behaviours, of which some include tipping. We show that tipping potential is strongly pre-conditioned by glacial and depositional inheritance, meaning that vulnerability is spatially heterogeneous in ways that cannot be inferred from contemporary climate forcing alone. The framework provides a basis for improved integration of permafrost instability into Earth system models, hazard assessment, and early warning systems.

Keywords: Thermokarst, Ground ice, tipping systems, Talik, Yedoma, Abrupt thaw

1 Introduction

The Arctic permafrost region covers approximately 25% of the Northern Hemisphere's land surface, with around 15% directly underlain by permafrost [1]. The terrestrial permafrost region stores an estimated 1,500 Pg of organic carbon, roughly twice the amount currently present in the atmosphere [2, 3]. The Arctic is warming three to four times faster than the global mean [4], increasing the risk of crossing permafrost-related tipping points [5], leading to the release of greenhouse gases into the atmosphere [6, 7]. Permafrost degradation is of interest both for its role in the Earth system and for its implications for infrastructure and settlement stability. Thaw-induced ground deformation can affect the integrity of buildings, transportation networks, pipelines, and other critical infrastructure, while also altering ecosystem processes and landscape dynamics [8, 9].

Following Lenton et al. [10], we define a tipping point as the point where small additional changes in one or several of the system conditions shift feedback mechanisms, such that positive feedbacks become dominant over stabilising negative feedbacks and drive self-propelling, substantial, widespread, and often difficult-to-reverse system changes. "Tipping system" refers to the broader class of systems that meet these criteria but where change in system state may occur at smaller spatial scales [11]. These definitions exclude processes that are merely non-linear, abrupt, or difficult to reverse in practice, unless they also exhibit internally generated feedback amplification capable of sustaining further change after the initial forcing threshold is crossed. A degradation process may exhibit partial irreversibility, weak or spatially constrained feedbacks, or propagation limited to specific geological and hydrological conditions. This ambiguity generates a range of interpretations when the framing is applied to permafrost, and a central issue has become the scale at which near-synchronous permafrost tipping could occur.

McKay et al. [12] distinguish between abrupt permafrost thaw as a regional impact tipping system with a central threshold estimate of approximately 1.5°C, and large-scale permafrost collapse as a potential global core tipping system with a central threshold of around 4°C. More recent work finds no evidence for self-amplifying processes operating across the whole permafrost region simultaneously, concluding instead that there are numerous local and regional tipping points that are crossed at different times and warming levels, producing cumulative rather than synchronous change

[13, 14]. However, it remains an open question whether on a regional scale, near-synchronous change could occur. For example, it is conceivable that certain areas of permafrost that share a common tipping threshold could pass it near-synchronously under spatially homogeneous forcing. Spatial heterogeneity and scale-dependence are therefore central challenges in assessing permafrost tipping behaviour. Whether a process qualifies as a tipping system depends not only on its feedback structure, but also on the spatial and temporal scale over which the dynamics operate.

Processes of permafrost change operate across spatial scales ranging from sub-metre ice-wedge networks to pan-Arctic areas of top-down thaw [15]. Some processes are abrupt yet weakly self-reinforcing, while others exhibit sustained localised feedback-driven propagation and strong hysteresis [7, 16]. Mechanisms vary according to whether they involve feedback amplification, structural irreversibility, or propagation beyond the initial disturbance site [10]. Treating these mechanisms collectively as a single tipping system therefore conflates fundamentally different dynamical behaviours [13, 14]. Conversely, dismissing permafrost as a global tipping point risks obscuring the fact that some local and regional processes may satisfy strict tipping-element system criteria [12].

In order to help resolve these challenges, a consistent framework is needed to assess whether specific permafrost processes qualify as having tipping dynamics, and to identify the state variables governing their behaviour. Existing reviews of permafrost change [15] and tipping system assessments [12, 13] do not provide such a framework.

Here, we propose a framework that distinguishes gradual, non-linear, threshold, and self-amplifying modes of permafrost degradation, and identifies the state variables governing transitions between them. We apply the framework to the principal mechanisms of permafrost thaw, including geomorphic, hydrological-thermal, surface energy, and biogeochemical processes, and assess which satisfy strict tipping system criteria. Finally, we discuss the implications for Earth system modelling, hazard assessment, and early warning.

2 Results

We classify permafrost degradation behaviour into four classes based on system dynamics rather than process identity alone (Figure 1). The same physical mechanism may occupy different classes under different combinations of permafrost property values. Consequently, a single landscape may contain processes belonging to multiple classes simultaneously.

Class I: Gradual response. System response is approximately proportional to external forcing with no internal amplification. If external forcing reverses, recovery broadly tracks reversed forcing magnitude and rate.

Class II: Reversible non-linear response. The system exhibits threshold-like or accelerated non-linear responses to forcing, but internal feedbacks are insufficient to sustain autonomous state transition. No strong hysteresis and recovery remains possible if the external forcing is reduced, but magnitude and rate of recovery may differ from that of the forcing.

Class III: Threshold system. Abrupt or discontinuous change is triggered once a critical condition is crossed, but self-reinforcing feedbacks are weak, spatially constrained, or dependent on continued external forcing. Continued evolution therefore requires sustained external forcing. Recovery is possible over longer timescales if external forcing decreases.

Class IV: Tipping system. Amplifying feedbacks drive self-sustaining state transition beyond a critical threshold, producing strong hysteresis and effectively irreversible change on policy-relevant human timescales, here defined as extending beyond multiple decades.

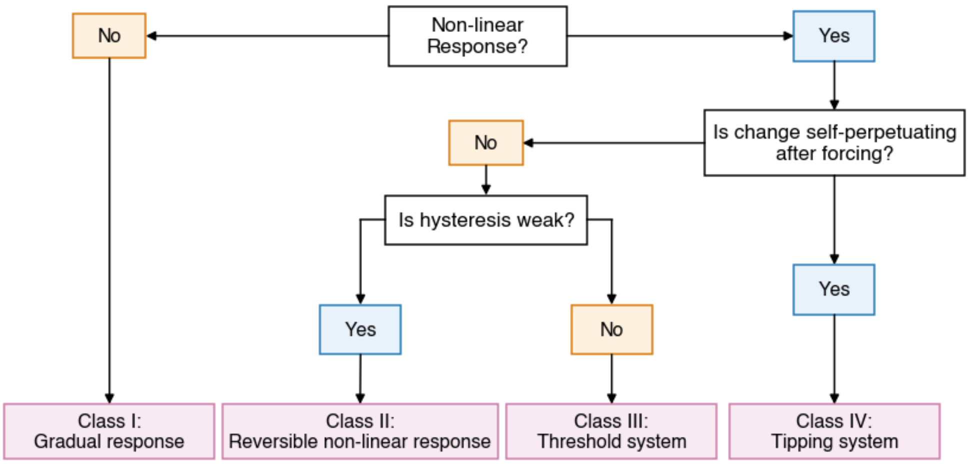

Fig. 1 Flowchart for categorising degradation mechanisms according to non-linearity, self-propagation, and hysteresis characteristics.

Accurate assignment of a process as a Class III Threshold System or a Class IV Tipping System requires explicit contrast with the gradual and reversible behaviours that precede tipping. In practice, the distinction turns on whether the system would continue evolving toward the new state if external forcing were held constant at the threshold level: Class IV Tipping Systems do; Class III Threshold Systems do not. Classes I (Gradual Response) and II (Reversible non-linear response) are included as a necessary baseline. Without this baseline, the terms "abrupt" and "irreversible" are applied inconsistently in the literature, which is part of the problem this framework is designed to address.

2.1 Permafrost environment variables

The variables below define the state space governing realised permafrost behaviour. Their values, interactions, and spatial configuration determine whether a given disturbance remains gradual, produces threshold behaviour, or develops into a self-sustaining tipping process. The variables are partially coupled and may co-evolve during degradation.

Table 1 Qualitative classification of permafrost behaviour regimes based on characteristic ranges of ice content, thermal margin, organic carbon density, structural integrity, and propagation potential. Qualitative descriptors indicate the typical state of each variable within a given class.

Variable	**Class I: Gradual response**	**Class II: Reversible non-linear**	**Class III: Threshold system**	**Class IV: Tipping system**
Ice content	Low	Low–moderate	Moderate–high	High
Thermal margin	Large	Moderate	Small	Near-zero
Organic matter density	Low	Low–moderate	Moderate	High
Structural integrity	Intact	Intact	Compromised	Lost
Vertical propagation	Low	Low	Moderate	High
Lateral propagation	Low	Low	Low	Moderate–high

Ice content is the dominant variable governing class membership within the framework. It determines the magnitude of volume loss on thaw, the strength of the latent heat barrier that must be overcome before structural change occurs, and the degree to which post-thaw collapse becomes irreversible [17]. In low ice-content terrain, thaw generally produces gradual subsidence with limited geomorphic consequence. In contrast, high ice-content permafrost can undergo abrupt, large-magnitude collapse once thermal thresholds are crossed, often resulting in effectively irreversible structural reorganisation [18].

High ice content also modifies thaw dynamics through latent heat effects. Large volumes of ground ice buffer warming by absorbing thermal energy during phase change, delaying threshold crossing. However, once thaw is initiated, the resulting structural collapse can accelerate further thaw through changes in hydrology, surface energy balance, and exposure of previously frozen material [18]. Consequently, increasing ice content tends to increase both the abruptness and irreversibility of permafrost degradation.

The spatial distribution of ground ice is determined primarily by depositional environment sedimentology, and glacial legacy rather than by contemporary climate alone [19]. As a result, landscapes exposed to similar climatic forcing may exhibit fundamentally different degradation trajectories depending on inherited ground-ice conditions.

2.1.1 Thermal margin

Although air temperature provides the primary climatic forcing, the transfer of atmospheric warming to the ground surface is strongly mediated by snow cover duration and depth [20], vegetation insulation [21], organic-layer thickness, soil moisture [22], and substrate thermal properties [23–25]. These factors regulate ground thermal regimes and can substantially amplify or buffer atmospheric forcing. Long-term ecological monitoring from Arctic tundra systems further demonstrates that progressive increases in ground temperature and active-layer thickness can drive substantial ecological change even in the absence of abrupt geomorphic disturbance, highlighting the importance of gradual top-down thaw processes in shaping ecosystem trajectories [26].

The thermal margin governs the sensitivity of permafrost to external disturbance. It emerges from the ground thermal regime established by both the current thermal state of the permafrost and the site conditions that regulate heat transfer, including snow cover, vegetation, and active-layer soil properties. Permafrost with a large thermal margin requires more sustained and substantial warming before critical thresholds are crossed, whereas systems with a small thermal margin and permafrost current temperatures close to 0°C can transition rapidly in response to a single anomalously warm season or disturbance event [27].

Thermal margin interacts strongly with ice content in determining system behaviour. Ice-rich permafrost with a substantial thermal margin may remain comparatively stable under moderate warming, whereas similarly ice-rich terrain with sensitive thermal regimes may be highly susceptible to rapid structural collapse and Class IV Tipping System transition [18]. Organic matter density of the permafrost itself also regulates the rate of thaw (see below) [28]. Neither variable alone is therefore sufficient to determine behaviour class. Instead, tipping potential emerges from their interaction. Consequently, landscapes exposed to similar climatic trajectories may exhibit markedly different rates and timings of permafrost degradation.

2.1.2 Organic matter density

Organic soils differ fundamentally from mineral soils in their thermal properties. Their thermal conductivity is substantially lower, particularly when dry or partially frozen [28], allowing thick organic layers to insulate underlying permafrost and maintain frozen ground under climatic conditions that might otherwise permit thaw [22] (see thermal margin above). Disturbance or degradation of this insulating layer reduces thermal margin, increases ground heat flux, and promotes further thaw, creating a positive feedback between surface disturbance and subsurface warming.

Abrupt thaw processes are estimated to affect less than 20% of the permafrost zone, yet may mobilise approximately half of all permafrost carbon [7]. This disproportionate impact reflects the frequent co-occurrence of high ice content and high organic matter density, illustrating why both variables must be assessed together within the framework.

Organic matter density influences both the thermal and biogeochemical dynamics of thaw [29]. Microbial decomposition of previously frozen organic matter releases heat, a process sometimes termed the “compost bomb” [30], which can locally enhance substrate warming and sustain thaw beyond that driven by surface forcing alone. Although typically weaker than hydrological or structural feedbacks, biochemical heating can reinforce thaw persistence in organic-rich terrain and sustain thaw propagation beyond the depth expected from surface forcing alone.

Important distinctions also exist between major carbon-rich permafrost substrates. Permafrost peatlands store large quantities of organic carbon across vertically extensive peat columns that are closely coupled to surface hydrology and active-layer dynamics [31]. Other carbon-rich permafrost substrates include Yedoma deposits or cryoturbated soil horizons [32, 33]. These permafrost soil types have similar C density to peatlands, but in mineral soil association and with less thermal buffering. As a result, peatland permafrost carbon can respond more slowly to external forcing, in the absence of nearby ground ice or lateral thermal propagation. In contrast, mineral-dominated carbon rich soils may be more vulnerable to both vertical and lateral heat propagation unless overlain by insulating organic layers [33]. These substrates therefore differ in the mechanisms through which carbon becomes accessible to decomposition.

As with ice content, organic carbon density is strongly influenced by depositional history and long-term landscape development [34]. Contemporary carbon accumulation in Arctic soils occurs [35], but is generally at rates far slower than potential carbon mobilisation under current warming trajectories. Carbon released during thaw may be respired and emitted to the atmosphere, transferred into aquatic systems, buried in sediments, or exported offshore as dissolved or particulate organic matter [36–39]. Organic carbon density therefore constrains the potential strength of local biogeochemical feedbacks, but should not be interpreted as a direct proxy for atmospheric carbon flux.

2.1.3 Structural integrity

Structural integrity describes the extent to which the physical architecture maintaining a permafrost system remains intact within a site to landscape-scale context. This includes factors such as connectivity of ice-wedge networks [40], peat plateau geometry, slope, and the stratigraphic continuity of ice-rich layers. Loss of structural integrity alters hydrological pathways, surface energy exchange, and mechanical stability, sometimes triggering transitions from gradual thaw to abrupt landscape change. This includes various landslide types, specifically retrogressive thaw slumps and active layer detachment slides.

The mechanical strength of frozen ground is governed by substrate composition, water content, temperature, and stress regime, which together determine compressive strength, shear resistance, creep behaviour, and deformation rates [41, 42]. Frozen soils derive strength from both the frictional and cohesive properties of the sediment matrix and the bonding effect of interstitial ice. In ice-rich terrain, deformation under sustained stress can occur over years to decades even in the absence of catastrophic failure, particularly on slopes or beneath external loading, such as infrastructure, vegetation, or sediment overburden.

Temperature exerts the dominant control on substrate strength. As ground temperature approaches 0°C, the proportion of unfrozen water increases rapidly, weakening ice bonds and substantially lowering both peak and residual shear strength [41]. The relationship is strongly non-linear, with mechanical strength declining sharply over a narrow temperature interval near the melting point. Salinity further modifies these dynamics by depressing the freezing point and increasing the unfrozen water content at a given temperature. Consequently, saline permafrost, which is common in coastal and marine sediment settings, often exhibits lower effective strength than freshwater permafrost under equivalent thermal conditions [42].

Slope angle exerts an independent control on structural integrity by governing the gravitational stress acting on thawed material, reducing the margin between applied stress and residual shear strength at a given ice content and thermal state. This is most visible in solifluction and gelifluction where surface velocity is constrained by slope angle, soil moisture and texture [43]. Centrifuge modelling of paired thawing slopes above and below a critical gradient shows that pore-water pressure rises rapidly on thaw in both cases, but only exceeds the threshold for failure on the steeper slope, with the resulting failure mode, ranging from mudflow to active layer detachment sliding, further shaped by clay content and consolidation history [44]. Slope therefore amplifies vulnerability already present through ice content and thermal margin, rather than being an independent trigger, explaining why near-identical ground conditions can produce markedly different outcomes depending on gradient alone.

2.1.4 Vertical propagation potential (hydrological connectivity)

Vertical propagation potential constrains the capacity of thaw to propagate downward through the soil column beyond the seasonally active layer. It is largely controlled by thermal-hydrological coupling between soil layers, partly interacting with the ground ice and organic matter density variables. As the active layer deepens, liquid water accumulates above the frost table, and under certain conditions the density contrasts between colder surface water and relatively warmer water at depth can drive density-driven convection [45]. This convective mixing delivers thermal energy directly to the frost table and accelerates downward thaw propagation at rates that significantly exceed those produced by conduction alone.

Talik formation represents the key outcome of high vertical propagation potential. Once a talik forms beneath a thermokarst lake or wetland, it insulates the underlying ground from winter refreezing and sustains year-round thaw. This constitutes a strong positive feedback as talik growth increases the volume of liquid water, increasing convective heat delivery and driving further talik expansion [46]. The process is effectively irreversible unless the surface water body drains or the overlying thermal regime changes substantially.

Vertical propagation potential is highest where the frost table is shallow, soil permeability is sufficient to allow water movement, and high organic content reduces thermal conductivity, slowing or preventing refreezing of the talik margins.

2.1.5 Lateral propagation potential

Lateral propagation potential refers to the capacity for permafrost disturbance to spread into adjacent terrain and is governed by thermal, structural, and hydrological processes. Thermal propagation occurs where heat conducts laterally from a thawed zone into neighbouring frozen ground, frequently via moving water, progressively reducing the thermal margin of neighbouring terrain. This process can exert a strong influence on subsurface ground temperatures, particularly at depth [47], yet lateral heat transfer remains poorly represented in many large-scale permafrost models, which prioritise vertical heat transfer [48]. Structural propagation occurs where physical failure in one part of a system destabilises adjacent material and triggers secondary collapse. This process is particularly important in sloped terrain, where initial headwall failure in a retrogressive thaw slump can remove support from upslope material and drive continued expansion without additional external forcing [49, 50]. Along permafrost coastlines, thermo-abrasional erosion can similarly drive rapid lateral retreat through coupled thermal and mechanical processes, with short-duration storm events capable of producing disproportionate geomorphic change [51].

Thermal erosion is defined as the erosion of ice-bearing permafrost by the combined thermal and mechanical action of moving water [52]. Such hydrological propagation exerts the greatest influence on lateral propagation potential. Meltwater flowing into adjacent terrain transfers thermal energy, erodes frozen material, and saturates previously stable ground, promoting further thaw and underpinning the lateral expansion of different types of thermokarst. The rate of propagation depends on meltwater volume, topographic gradient, and the ice content of the substrate into which thaw propagates. Hydrological propagation potential is itself constrained by topography and relief [53], permafrost continuity, soil permeability, and the configuration of drainage pathways between landscape units [54]. In highly dissected terrain with efficient drainage, meltwater is routed away from adjacent frozen ground, limiting lateral spread, whereas in low-relief terrain with poor drainage, retained meltwater saturates neighbouring ground and substantially increases the potential for rapid lateral expansion.

2.2 Mechanisms of permafrost degradation

Permafrost degradation processes operate across a variety of environments and spatial and temporal scales (Figure 2), with many occurring in overlapping geomorphic and hydrological settings. These processes commonly involve degradation of ground-ice structures, reorganisation of subsurface thermal and hydrological regimes, or thermokarst development. Not all consequential permafrost degradation occurs through abrupt collapse, however. Gradual active layer deepening exposes ever more previously frozen soil organic matter, and remains a main pathway of the permafrost-carbon feedback [55]. Long-term ecological monitoring from Arctic tundra systems further demonstrates that progressive increases in ground temperature and active-layer thickness can drive substantial vegetation and ecosystem change even in the absence of abrupt geomorphic disturbance [26]. Such gradual top-down thaw processes are particularly important at broad spatial scales and may drive widespread ecosystem reorganisation before more abrupt structural thresholds are crossed. These observations are consistent with the Class I gradual top-down thaw pathway identified in Figure 1, where persistent thermal change produces widespread ecological responses without requiring threshold-driven structural collapse. Rather than functioning as a coherent system with a single threshold, permafrost is better understood as a heterogeneous mosaic of locally distinct tipping systems whose behaviour depends on the specific combination of state variables present at each site [13]. Consequently, the aggregate global response emerges through the cumulative crossing of many site- to regional-scale thresholds at different times and warming levels, rather than through a synchronous pan-Arctic transition. In systems where degradation is associated with structural collapse, particularly in ice-rich terrain, Class IV transitions are effectively irreversible on human timescales even where climatic conditions could theoretically permit partial thermal recovery.

Fig. 2 Permafrost change processes plotted by scale of occurrence and average feature size, colour-coded by behaviour class as defined in this study. Class IV processes are largely confined to the regional scale column, consistent with the requirement for hydrological connectivity between landscape units to sustain lateral propagation. Pan-Arctic processes are Class I-II, reflecting large-scale gradual responses to forcing. Scale of occurrence here denotes individual feature footprint, not the extent of spatial clustering among multiple instances. Note that coastal erosion occurs across all scales and feature sizes and so is not included in this figure. TK = Thermokarst. Adapted from Webb et al. [15] to show permafrost degradation class, rather than ecosystem change.

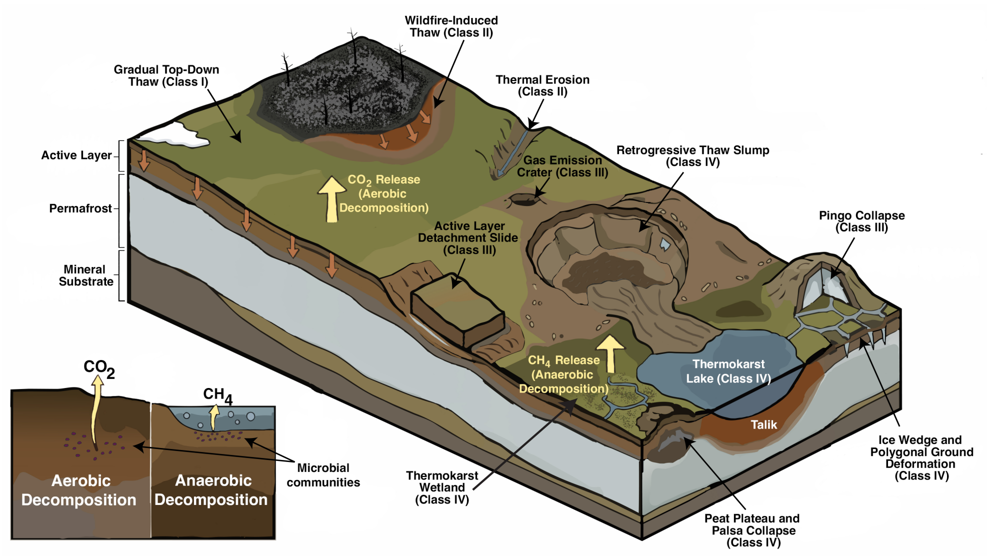

Fig. 3 Schematic diagram demonstrating permafrost degradation processes, their classes and feedback mechanisms.

2.3 Class I: Gradual response

2.3.1 Gradual top-down thaw

Change under gradual top-down thaw is proportional to forcing, spatially coherent, and does not involve structural threshold behaviour or self-amplifying feedbacks. It is the dominant mode of permafrost change in mineral soils with low ice content and is the process most commonly represented in Earth system models [56]. As air temperatures rise, the seasonal thaw front penetrates progressively deeper into the ground, increasing active-layer thickness and expanding the volume of annually thawed soil (Figure 3). In mineral soils with low ice content, thaw-induced volume loss is limited, surface subsidence remains minor, and drainage pathways are not substantially reorganised. The process is therefore assigned to Class I: Gradual Response because the system response remains continuous and approximately proportional to external forcing, without the threshold dynamics of internal feedbacks required to produce abrupt state transitions. This assignment reflects low ice content and a large thermal margin. As excess ice is limited, there is little latent heat barrier to overcome and no structural threshold for the system to approach, so the response aligns with forcing, rather than accelerating towards a critical point.

Despite the absence of major geomorphic collapse, gradual top-down thaw can still drive substantial ecological and biogeochemical change over decadal timescales. Long-term Arctic tundra monitoring has demonstrated that progressive increases in ground temperature and active-layer thickness are associated with widespread shifts in vegetation composition and ecosystem structure, even where abrupt thermokarst development is absent [26].

Top-down thaw can also act as a precursor to higher-class processes. In terrain with moderate or high ice content, progressive active layer deepening increases the probability that thaw will reach ice-rich layers, after which Class III: Threshold System or Class IV: Tipping System transitions may be initiated. When the upper permafrost is ice-rich, active layer deepening is often also associated with widespread gradual ground subsidence, which may not manifest as distinct thermokarst landforms [57]. The classification of top-down thaw as Class I therefore applies specifically to low ice-content settings and should not be generalised to ice-rich terrain, where similar climatic forcing can produce fundamentally different outcomes.

2.4 Class II: Reversible non-linear response

2.4.1 Wildfire-induced thaw

Wildfire removes the insulating organic layer and vegetation that moderates ground temperature, often causing rapid and substantial deepening of the active layer in the years immediately following burning (Figure 3) [58, 59]. In many tundra systems active-layer thickness can sometimes partially or fully recover over subsequent decades provided that underlying permafrost structure remains intact and self-sustaining thaw processes are not initiated [60]. This potential for both rapid degradation, but also recovery under moderate disturbance conditions places wildfire-induced thaw in Class II: Reversible non-linear response.

The magnitude and persistence of post-fire thaw depend strongly on combustion severity, organic-layer loss, hydrological change, vegetation recovery, and pre-existing permafrost conditions. Low- to moderate-severity burns may produce transient thermal perturbations without major geomorphic reorganisation, whereas severe fire can reduce thermal margin and structural integrity sufficiently to initiate thermokarst development or persistent talik formation. In boreal forest and discontinuous permafrost regions, these processes can drive extensive and long-lasting permafrost degradation[60].

Fires can reduce the thermal offset or structural integrity sufficiently to initiate thermokarst features that persist and expand independently of subsequent fire return intervals. In these scenarios, wildfire acts as a trigger for Class III: Threshold System or Class IV: Tipping System transitions, rather than a Class II process in its own right. The assignment to Class II therefore applies to the thermal perturbation in terrain where the underlying permafrost can sustain recovery, not to fire events in organically-rich terrain. It has also been shown that fire recovery may actually increase the landscape carbon storage [61]. Wildfire should therefore not be understood as a single permafrost response class, but as a disturbance capable of producing outcomes that range from reversible thermal perturbation to irreversible structural transition depending on landscape context. The assignment to Class II applies specifically to systems in which post-fire recovery remains probable and thaw does not become self-propagating.

2.4.2 Thermal erosion

Thermal erosion describes the removal of frozen sediment by flowing water through the combined action of mechanical erosion with thermal energy transfer from relatively warm surface water [62]. Given this broad definition, thermal erosion is active in the formation of many of the other classes identified here. It occurs within stream channels, gully networks, and exposed slopes following vegetation loss or surface disturbance, but it also drives the lateral expansion of thermokarst lakes as well as coastal erosion.

Thermal erosion rates commonly increase disproportionately during warm periods or high-discharge events, reflecting the strong coupling between hydrological energy and thaw processes. Where sediment supply is limited and channels can stabilise following disturbance, the process remains broadly reversible and is therefore assigned to Class II: Reversible non-linear response.

The behaviour of thermal erosion depends strongly on substrate properties. In terrain containing ice-rich sediments or massive ground ice, erosion can breach the latent heat barrier and rapidly accelerate thaw, destabilising adjacent material and promoting headwall retreat. Under these conditions, localised channel erosion may transition into self-sustaining retrogressive thaw slump dynamics characteristic of Class III: Threshold System or Class IV: Tipping System behaviour. The progression from relatively contained (Class II) thermal erosion to large-scale structural collapse (Class IV) illustrates how similar surface process can occupy fundamentally different behavioural classes depending on ice content and structural integrity.

2.4.3 Thermokarst pits and troughs

Thermokarst pits and troughs are micro-scale features which form where localised thaw of ground ice produces surface subsidence. In low ice-content terrain, the resulting features are limited in extent and do not expand substantially once the initial ice has melted. Surface drainage may be locally altered, but without sustained positive feedbacks the system stabilises at a new lower surface elevation. Thermokarst troughs and pits can develop within old thermokarst lake basins [16]. These landforms are classified as Class II: Reversible non-linear response as the response is non-linear given the abruptness of initial subsidence, but the transition is not self-amplifying and recovery of surface hydrology is possible over decadal to centennial timescales. Where pits and troughs form in highly ice-rich terrain with favourable hydrological connectivity, they can act as nucleation sites for thermokarst lake expansion, in which case the initiating event is Class II but the subsequent trajectory enters Class IV: Tipping System dynamics.

2.4.4 Thermokarst water track formation (thermal erosion gullies)

Thermokarst water tracks are elongated drainage features that develop on low-gradient permafrost slopes where lateral soil water flow concentrates in topographic lows [63]. They are associated with locally elevated soil temperatures, greater active layer depths, and higher rates of organic matter decomposition relative to surrounding undisturbed terrain. They are often associated with ice-wedge polygon networks [16]. Their formation is non-linear as once a preferential flow path is established, positive feedback between soil warming and increased drainage efficiency tends to deepen and widen the feature. However, water tracks are constrained by topography and do not generally expand beyond the boundaries of the drainage network that feeds them. The process is therefore considered as Class II: non-linear and self-reinforcing within limits, but not unbounded in lateral propagation and partially reversible if the hydrological forcing is altered.

2.5 Class III: Threshold system.

2.5.1 Active layer detachment slides

Active layer detachment slides (ALDS) (Figure 5A) are localised slope failures where the seasonally thawed active layer detaches and slides downslope along the interface with still-frozen permafrost [64]. They are often tens to hundreds of metres in length, and are most common on moderate slopes underlain by ice-rich silts or peats. Initiation is generally associated with rapid thaw, intense rainfall, or both, which elevate pore water pressures within the active layer and reduce effective shear strength [65]. These conditions may also be initiated by wildfire [66, 67]. Once the shear resistance of the affected slope is exceeded, the thawed layer can move over the relatively impermeable frozen substrate. Lateral propagation is assigned as low, distinguishing ALDS from the moderate–high propagation of Class IV: Tipping System mass-wasting features. Unlike e.g. RTSs, ALDS do not usually expose massive ground ice or generate sustained headwall retreat. Their dynamics are therefore more episodic than propagative. Movement often occurs over days to weeks during particularly warm or wet summers, after which they may stabilise until subsequent extreme conditions reactivate or expand them. Although repeated failures can incrementally widen scars, the process lacks the prolonged internal feedback characteristic of RTS headwall expansion.

2.5.2 Gas emission craters and pingo collapse

In some settings, permafrost degradation can also produce abrupt gas release events. Gas emission craters observed on the Yamal Peninsula have been interpreted as the result of pressurised gas accumulation beneath impermeable frozen layers, followed by explosive rupture [68]. Related processes have been proposed for open-system pingo collapse, where gas and water migration destabilise ice-rich cores [69]. These phenomena reflect localised structural failure rather than gradual system weakening, and gas emission craters are only found in areas with high geological methane concentrations.

2.5.3 Coastal erosion

Coastal erosion is strongly influenced by increased storm frequency and intensity in the Arctic Ocean [70], declining sea-ice extent and duration[71], and substantial geomorphic and sedimentological variability along permafrost coastlines [72]. Arctic coastal erosion has increased in recent decades, largely driven by reduced sea-ice cover increasing wave exposure and extending the open-water season, enhancing thermal and mechanical erosion of frozen coastal bluffs [73]. In addition to atmospheric warming and sea-ice decline, relative sea-level rise enhances coastal instability by increasing wave exposure and promoting sustained bluff erosion, even where climatic warming alone would be insufficient to drive rapid retreat. Although coastal erosion is often a symptom of ongoing permafrost degradation, it can also amplify thaw locally by exposing ice-rich sediments, promoting block failure and mass wasting, and steepening drainage paths that accelerate RTS development.

Structural integrity is assigned as compromised, rather than lost, reflecting the dependence of retreat rates on highly episodic erosion dynamics. High-resolution drone surveys have shown that nearly one-third of annual coastline retreat occurred during a single four-day storm event [51], illustrating how abrupt geomorphic change can arise from the interaction between gradual climatic warming and short-duration hydrodynamic forcing. Coastal thermo-abrasion therefore represents an important coupling between thermal, hydrological, mechanical, and sea-level-driven degradation processes across Arctic permafrost landscapes.

2.6 Class IV: Tipping system

2.6.1 Thermokarst wetland formation

Thermokarst wetlands form where thaw of ice-rich ground causes surface subsidence, ponding, and persistent waterlogging. They can form in different types of soil and sediment, but frequently form within permafrost peatland complexes [31]. Unlike thermokarst lakes, they do not typically develop standing water bodies deep enough to drive talik formation. Nevertheless, the resulting saturated surface conditions can generate persistent positive feedbacks that promote continued thaw and inhibit permafrost recovery [16].

The loss of the original vegetation and surface structure reduces albedo and alters snow accumulation and surface energy exchange, often increasing near-surface ground conditions and increasing active layer thickness [74]. Saturated soils also reduce thermal buffering associated with intact vegetation and organic-layer structure, reinforcing thaw persistence. If wetland formation is triggered by wildfire, this can further accelerate these transitions by removing insulating vegetation and organic layers, reducing thermal margin, and increasing ground heat flux into underlying permafrost. In ice-rich terrain, these coupled hydrological, ecological, and thermal changes can drive sustained landscape transition toward wetter, non-permafrost states.

2.6.2 Thermokarst lake formation

Thermokarst lakes form where thaw of ice-rich permafrost causes substantial surface subsidence and ponding, allowing standing water to accumulate. Once established, these water bodies enhance ground heat transfer through the high heat capacity and convective mixing of liquid water, promoting talik formation and sustained downward thaw propagation [75, 76]. This creates an amplifying feedback in which thaw promotes water accumulation, which in turn accelerates further thaw (Figure 4).

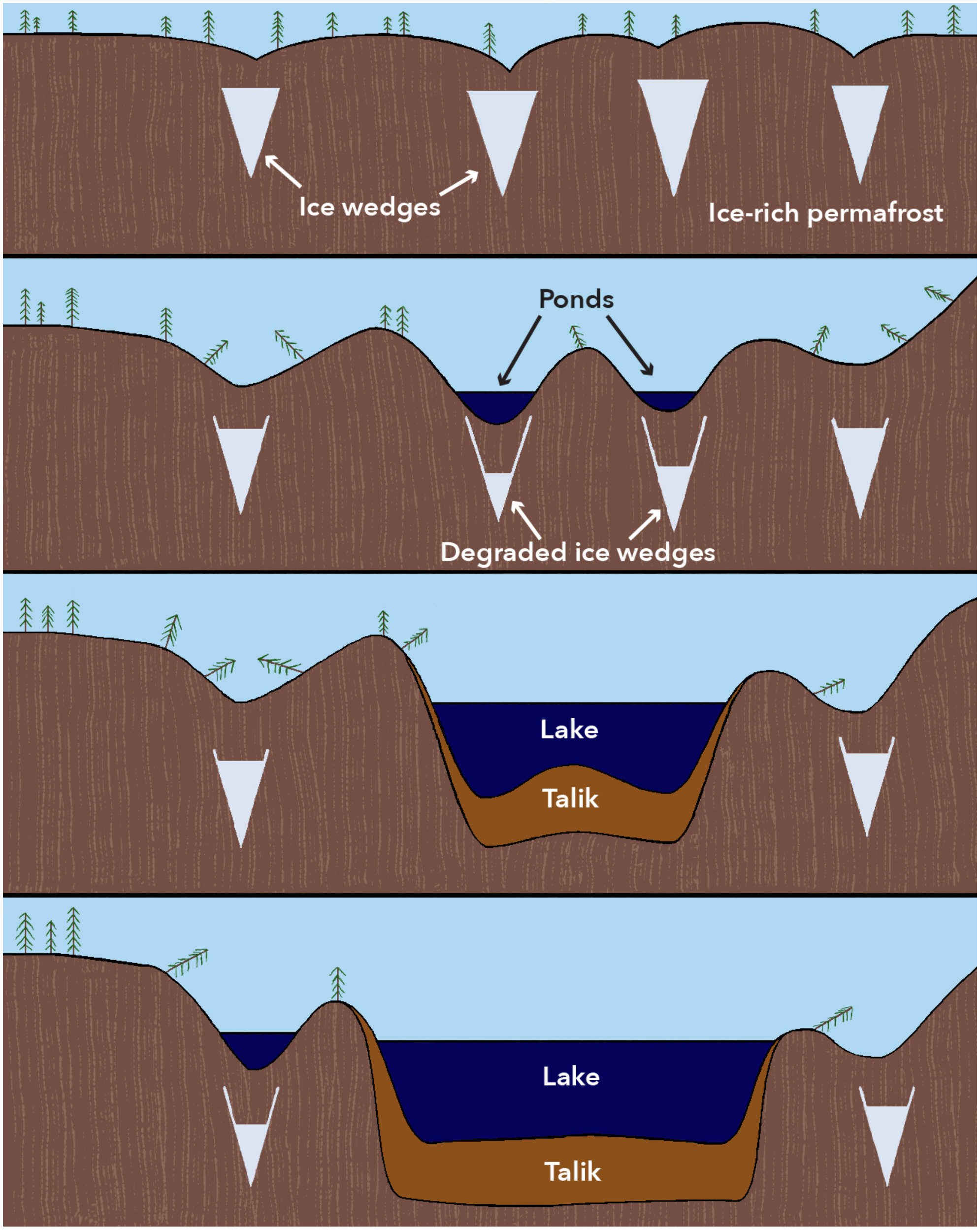

Fig. 4 Thermokarst lakes expand through thaw-driven subsidence and positive feedbacks between surface water and permafrost degradation. Adapted from Bouchard et al. [77].

Many thermokarst lake systems initiate abruptly once local thresholds related to ground-ice content, hydrology, surface disturbance, or inherited glacial and depositional conditions are crossed, rather than through prolonged gradual weakening. Recovery of large thermokarst systems to their original permafrost and ecological state is rare and typically occurs only over very long timescales [16]. Extensive thermokarst lake systems formed during the last deglaciation transitioned into stable permafrost and net carbon sinks over time [78]. The cyclic nature of thaw lake formation is illustrated by the widespread occurrence of drained lake basins across the circumpolar region [79]. The strong influence of local geological and hydrological controls also complicates attribution and limits the transferability of thermokarst-based early warning indicators between regions.

2.6.3 Retrogressive thaw slumps (RTS)

RTSs (Figure 5B) are mass-wasting features that develop predominantly on ice-rich slopes where exposure of massive ground ice initiates rapid headwall retreat, sediment mobilisation, and downslope transport [80]. Individual RTSs are typically smaller than < 1 km^2, but can expand rapidly once initiated [81, 82].

RTSs are classified as Class IV: Tipping System because headwall retreat exposes previously frozen and ice-rich material, promoting continued thaw and sustained expansion through self-reinforcing thermal and mechanical feedbacks [83, 84]. Once initiated, slump growth can continue for years to decades without requiring repeated triggering events. Structural integrity is assigned as lost and lateral propagation as moderate–high because headwall retreat exposes previously frozen, ice-rich material that promotes further thaw, sustaining expansion through self-reinforcing thermal and mechanical feedbacks without need for renewed external triggering, in direct contrast with the episodic reactivation that characterises ALDS.

RTSs commonly occur in spatial clusters associated with specific geomorphological and sedimentological settings characterised by high ground ice content. These include glacial moraines in the Canadian High Arctic [85], Yedoma terrain containing thick ice wedges, and fine-grained marine sediments uplifted following deglaciation that subsequently developed ice-rich epigenetic permafrost [86]. Such clustering suggests that shared geological conditions can bring multiple sites close to a common instability threshold increasing the likelihood of synchronous landscape-scale change under climatic forcing.

While RTS areas are currently expanding, there is prevalent evidence of stabilised RTS landforms, with stabilisation occurring if exposed ground ice completely melts or the exposed ice is re-buried and thermally insulated [50].

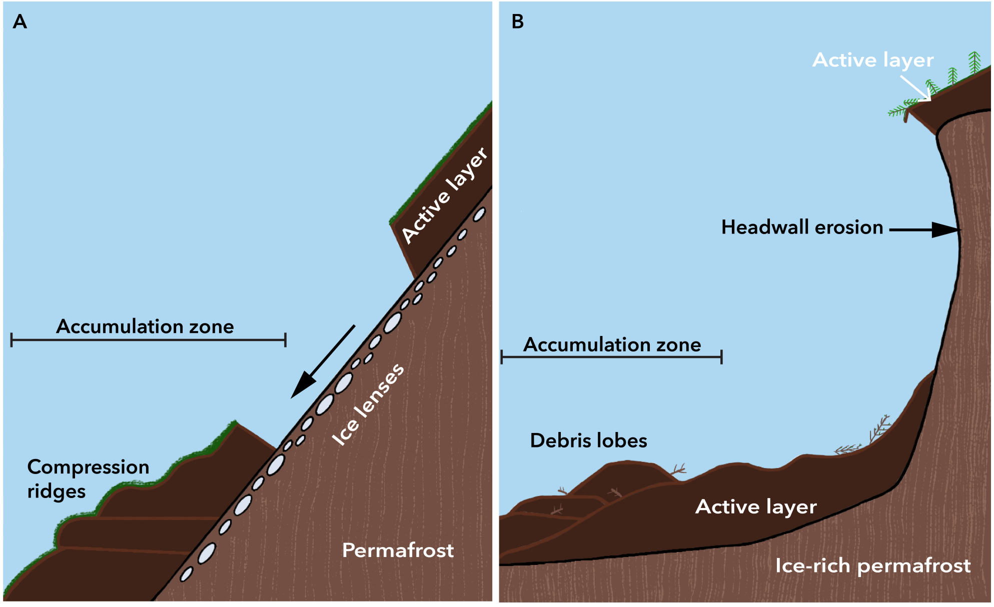

Fig. 5 Retrogressive thaw slumps propagate through self-reinforcing headwall retreat, whereas active layer detachment slides produce episodic slope failures. A) Active layer detachment slide: Downslope movement of the thawed active layer over underlying permafrost, triggered by elevated pore water pressures from melting ice lenses that reduce shear strength. B) Retrogressive thaw slump: Mass wasting feature formed by thawing of ice-rich permafrost, often initiating as a headwall collapse and propagating. Adapted from van Huissteden [64].

2.6.4 Ice-wedge and polygonal ground degradation

Ice wedges are vertically-orientated bodies of ground ice that form through repeated cycles of thermal contraction cracking and subsequent infilling. They typically range from millimetres to several metres in width and can extend to depths of around 10 m [40, 87]. Ice wedges underpin the polygonal ground that characterises many lowland Arctic permafrost landscapes [88].

When ice wedges thaw, the resulting loss of ground ice volume reduces structural support within near-surface permafrost, leading to trough subsidence, collapse of polygon rims, and reorganisation of surface drainage pathways. These changes often promote surface ponding and the development of small thermokarst features, making ice-wedge degradation an important mode of landscape-scale ground deformation in ice-rich, low-relief terrain [89].

In polygonal tundra, degradation can also alter hydrological connectivity between adjacent polygons. Once thaw reaches a critical level, landscapes may cross a percolation threshold where water is able to spread laterally across previously disconnected polygon networks [90]. This can produce abrupt flooding or drainage transitions across large areas of tundra. Although this behaviour is strongly threshold dependent, it remains uncertain whether the associated feedbacks are sufficiently self-sustaining to consistently satisfy Class IV tipping criteria. We provisionally assign ice-wedge degradation to Class IV where polygon network connectivity is established, while noting that in systems where this connectivity remains limited, Class III may be more appropriate. Resolution would require field studies comparing feedback persistence under reduced forcing across contrasting hydrological settings.

2.6.5 Talik formation and drainage reorganisation

Taliks are zones of unfrozen ground that persist year-round within otherwise frozen permafrost terrain. They commonly form beneath lakes, wetlands, or areas of sustained hydrological disturbance where summer heat input exceeds winter refreezing capacity [45]. Once established, taliks can strongly accelerate vertical thaw propagation by maintaining hydraulic connectivity and enabling convective heat transfer within the soil column.

Abrupt talik formation is associated with a threshold transition in subsurface thermal-hydrological dynamics. As thaw depth and soil water increase, density-driven convection can develop within saturated sediments, transferring heat downward far more efficiently than conduction alone [45]. This transition enhances thaw persistence and can sustain continued permafrost degradation even under relatively modest additional forcing. Talik development also commonly reorganises local drainage networks, altering hydrological connectivity and promoting further thaw in adjacent terrain.

High vertical propagation is assigned because talik-mediated thaw enhances thaw persistence and can sustain continued permafrost degradation even under relatively modest additional forcing, meeting the Class IV: Tipping System criteria.

2.6.6 Peat plateau and palsa collapse

Peat plateaus and palsas are ice-rich permafrost landforms usually found in discontinuous permafrost near the margins of the permafrost zone, making them particularly sensitive to atmospheric warming and changes in precipitation. Both landforms rely on perennially frozen cores for structural stability. Peat plateaus are generally extensive, flat-topped features elevated above surrounding wetlands, whereas palsas are smaller and typically form dome-shaped mounds [91].

Multiple studies suggest that many peat plateaus and palsas are undergoing sustained degradation [31, 92–94]. In some areas this process may have been ongoing for more than a century, reflecting long-term landscape adjustment rather than short-term climatic variability [94]. Collapse typically involves progressive surface lowering, fragmentation into smaller units, and water ponding at the margins, culminating in effectively irreversible loss of permafrost [95]. Palsas appear to degrade more rapidly than peat plateaus, likely reflecting their smaller size and greater sensitivity to changes in ground temperature and hydrology [96]. Based on paleoevidence from previous peat plateau and palsa collapse, development into stable peatlands with a net climate cooling effect can be expected after a period of several hundred years [31].

3 Discussion

The biogeochemical consequences of permafrost thaw represent the principal mechanism through which locally and regionally confined tipping behaviour becomes relevant to the global climate system, via organic carbon mobilisation, microbial activation [97], and methane release [98–101]. The magnitude of these feedbacks depends on the geomorphological pathway of thaw and whether the newly available organic matter decomposes under aerobic or anaerobic conditions; they are not simply proportional to the volume of ground thawed.

Gradual top-down thaw (Class I) is more likely to expose organic matter progressively within a well-drained, oxygenated active layer, favouring aerobic decomposition and CO_2 release. In contrast, tipping systems (Class IV), frequently generate saturated or submerged conditions, either directly, as in thermokarst lake and wetland formation, or as a secondary consequence of structural collapse and drainage reorganisation, as in RTSs and talik development. These anoxic environments favour methanogenesis, meaning that an equivalent quantity of mobilised carbon may produce substantially greater radiative forcing when released through a tipping response than through gradual or reversible thaw processes.

Thermokarst lakes illustrate the complexity of these feedbacks because they can function simultaneously as carbon sources and sinks. Lake formation can release substantial quantities of CO_2 and CH_4 [102, 103], and this process has been found to have contributed to the climate warming at the Pleistocene-Holocene transition [104]. However, established lakes also accumulate new organic carbon through nutrient release and slow decomposition in cold, anoxic bottoms, and lake drainage can substantially reduce methane emission by permitting permafrost re-establishment [78, 79, 105]. Thermokarst lake development in Yedoma terrain can produce disproportionately large greenhouse gas emissions because thaw can initiate deep talik formation and reactivate previously inaccessible methane-rich carbon reservoirs [103, 106].

RTSs can also expose deep, previously undisturbed carbon pools at rates far exceeding gradual thaw, and have been shown to release greenhouse gases to the atmosphere at rates disproportionate to the area affected [107].

In organic-rich substrates, it is also possible for microbial decomposition of newly thawed material to release heat in a self-reinforcing process termed the "compost bomb" [30]. The microbial communities responsible for this decomposition also differ between the seasonal thaw layer and previously frozen permafrost [108], meaning that the biogeochemical response to thaw is determined by both the physical class of the process and the taxonomic composition of the microbial assemblage exposed. Consequently, assessments of permafrost carbon-climate feedbacks based solely on thaw extent risk misrepresenting the resulting atmospheric impact.

The importance of these distinctions is reinforced by the scale dependence of permafrost tipping behaviour. A process may represent a tipping system locally while failing to constitute a larger-scale, pan-Arctic transition. Local collapse events may initiate Class IV: Tipping System behaviour, but whether an individual event propagates beyond its initiation site to landscape scale depends largely on hydrological connectivity between landscape units and on the ice content of the terrain immediately adjacent to the initiation site (Section 2.1). Under continued warming, tipping behaviour may not always be limited to local scale. Areas currently in Class I or Class II may transition to higher classes as thermal margins decrease. This does not imply a global tipping point but it does mean that the fraction of the permafrost domain capable of Class IV transitions will increase progressively under sustained warming, with corresponding increases in the rate of irreversible structural change. The aggregate global signal is therefore better understood as the cumulative sum of many independently triggered, degradation events, rather than as a single system-wide threshold response [13, 14].

The spatial heterogeneity that drives this is largely dependent on geological legacy. Although glaciers and permafrost have historically been viewed as mutually exclusive, there is evidence that past glaciation affects permafrost characteristics [34]. Therefore, tipping potential in permafrost systems may be heavily pre-determined by glacial and depositional legacy, rather than by contemporary climate forcing alone. Ice content is inherited from past glaciation and is only slowly modified by subsequent climate. The distribution of Yedoma deposits, ice-rich morainal terrain, and marine sediments uplifted following deglaciation reflects depositional histories extending back to the Last Glacial Maximum and beyond, and this past continues to influence the spatial pattern of present-day permafrost vulnerability [34], as well as the size and distribution of the carbon stocks available for mobilisation [109]. Therefore, the spatial distribution of tipping-capable systems is not uniform across the permafrost domain and cannot be inferred from contemporary climate forcing alone. Past geomorphic processes determine drainage and relief, and lithology further influences structural stability, so the same climatic trajectory can produce markedly different outcomes depending on inherited geological context [110]. Understanding permafrost instability therefore requires a landsystem approach that integrates geological inheritance with present-day thermal and hydrological conditions [111].

This variability that characterises permafrost means that Class IV: Tipping System transitions will occur at different global temperatures in different regions, with most landscape change remaining non-propagating even in nominally similar terrain. Genuinely large-scale, self-sustaining collapse, such as at the Batagaika Crater, is confined to specific combinations of ice content, disturbance history, and slope hydrology that are not representative of the permafrost domain as a whole. Beyond carbon, permafrost contains legacy pollutants, including mercury [112], and because contaminant mobilisation is also likely to be class-dependent, the framework developed here is applicable to Arctic environmental health and contaminant risk assessment as well as to climate projection.

These findings carry direct implications for Earth system modelling, hazard assessment, and the framing of permafrost-related climate risk. Most Earth system models primarily represent gradual top-down thaw and therefore capture Class I behaviour reasonably well. However, many Class III: Threshold System and Class IV processes operate at spatial scales below the resolution of global climate models and depend on local hydrological, geomorphological, and geological conditions that are not explicitly represented, therefore the processes most likely to produce abrupt, high-impact carbon release are poorly captured by the models used to project future carbon-climate feedbacks [7]. As ESMs typically allow thermal recovery once forcing decreases, whereas

Class IV: Tipping System transitions do not, models built on vertical diffusion alone are structurally predisposed to overestimate the recoverability of permafrost carbon stocks under mitigation scenarios, since they have no mechanism by which a transition can become irreversible independent of the forcing that caused it.

The state variables identified here offer one route to closing this gap. Ground ice content and lateral propagation potential are not explicitly represented in current ESMs, removing any mechanism by which the models can distinguish terrain capable of Class IV transition from terrain that will only ever undergo Class I gradual response under the same forcing. These state variables are observable in principle, for example ground ice content is captured at coarse resolution by existing products [113, 114] and have been combined with geomorphological data to produce finer-resolution geohazard products [115]. However, current datasets remain far coarser than the metre scale at which key variables actually operate. Closing this gap will require integrating high-resolution remote sensing products with the coarser datasets, rather than relying on either alone.

A further constraint on closing this observational gap is geopolitical rather than technical. Approximately 60% of global permafrost lies within Russian territory, and since 2022 the collapse of ground-based monitoring collaboration and data-sharing between Russian and international research networks has produced substantial, and likely growing, gaps in the in-situ observations needed to calibrate and validate remote sensing products [116]. Satellite coverage of these regions continues, but without ground-truth data to constrain uncertainty. The practical value of that coverage for parameterising the state variables identified here is therefore reduced. This means that model improvements of the kind proposed here are likely to remain more workable in well-monitored regions of North America and Scandinavia than across the ice-rich Siberian terrain, including much of the Yedoma domain, that this framework identifies as disproportionately important for Class IV behaviour. However, the framework's state variables may provide a specific, physically grounded target for future integration efforts, clarifying which properties any sub-grid parameterisation scheme would need to resolve, even where the observational basis to do so at the required resolution and coverage does not yet fully exist.

The framework presented here is qualitative rather than quantitative, and class assignment for a given site relies on judgement informed by the available observational and modelling evidence. Attribution of observed permafrost degradation to climate change versus non-climatic disturbance is not always possible, and this framework does not resolve that problem. Wildfire, infrastructure disturbance, and wildlife disturbance can each trigger Class III or Class IV behaviour in terrain that would not otherwise cross a threshold under climate forcing alone. The expansion of beaver populations across the Arctic, and the associated construction of dams that alter hydrological connectivity, is one example of a non-climatic driver of talik formation and thermokarst development that is largely absent from existing permafrost tipping assessments [117]. Although the classification can be applied regardless of the ultimate driver of disturbance, the source of triggering has direct consequences for attribution, monitoring design, and policy response that fall outside the scope of a purely physical classification framework.

More broadly, this framework provides a structured basis for distinguishing between gradual change, threshold responses, and genuinely self-sustaining tipping dynamics within permafrost systems, addressing longstanding ambiguity in the use of terms such as "abrupt", "irreversible", and "tipping point". By requiring classification to be based on system behaviour under specific environmental conditions, rather than on processes in isolation, the framework helps to separate transient disturbance responses from sustained state transitions driven by reinforcing feedbacks. Our synthesis suggests that genuinely propagating tipping behaviour is likely restricted to a relatively limited subset of permafrost environments characterised by high ground-ice content, low thermal margins, strong hydrological coupling, and the capacity for lateral or vertical feedback propagation, conditions that occur disproportionately within Yedoma terrain, ice-rich morainal landscapes, degrading peat plateaus and palsas, and some thermokarst systems. In contrast, many widely observed forms of permafrost degradation appear to remain spatially constrained, episodic, or externally forced, despite producing substantial local environmental impacts. The framework therefore has implications beyond geomorphological classification alone as it provides a basis for improving interpretation of early warning signals, evaluating the representation of abrupt thaw processes within Earth system models, and distinguishing between localised landscape instability and larger-scale climate-relevant tipping behaviour, and also highlights the need for future permafrost research to move beyond binary distinctions between "gradual" and "abrupt" change toward a more process-explicit understanding of stability, reversibility, and feedback strength across Arctic landscapes.

Supplementary information.

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Declarations

Some journals require declarations to be submitted in a standardised format. Please check the Instructions for Authors of the journal to which you are submitting to see if you need to complete this section. If yes, your manuscript must contain the following sections under the heading 'Declarations':

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