Lake and drained lake basin systems in lowland permafrost regions

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Abstract | The formation, growth and drainage of lakes in Arctic and boreal lowland permafrost regions influence landscape and ecosystem processes. These lake and drained lake basin (L-DLB) systems occupy >20% of the circumpolar Northern Hemisphere permafrost region and ~50% of the area below 300 m above sea level. Climate change is causing drastic impacts to L-DLB systems, with implications for permafrost dynamics, ecosystem functioning, biogeochemical processes and human livelihoods in lowland permafrost regions. In this Review, we discuss how an increase in the number of lakes as a result of permafrost thaw and an intensifying hydrologic regime are not currently offsetting the land area gained through lake drainage, enhancing the dominance of drained lake basins (DLBs). The contemporary transition from lakes to DLBs decreases hydrologic storage, leads to permafrost aggradation, increases carbon sequestration and diversifies the shifting habitat mosaic in Arctic and boreal regions. However, further warming could inhibit permafrost aggradation in DLBs, disrupting the trajectory of important microtopographic controls on carbon fluxes and ecosystem processes in permafrost-region L-DLB systems. Further research is needed to understand the future dynamics of L-DLB systems to improve Earth system models, permafrost carbon feedback assessments, permafrost hydrology linkages, infrastructure development in permafrost regions and the well-being of northern socio-ecological systems.

Periglacial
Processes influenced by intense freeze–thaw and/or permafrost.

Permafrost is any Earth material that remains at or below 0 °C for two or more consecutive years[1]. Estimates indicate that permafrost underlies 11–15% of Arctic and boreal regions, and occurs across 15–24% of the Northern Hemisphere land mass[2–5] (FIG. 1). Northerly (>60°N), lowland regions (<300 m above sea level) account for ~60% of the Arctic and boreal permafrost region (FIG. 1). Modern-day permafrost distribution is a function of current climate conditions, the legacy of cold and warm periods in the past, the interactions between atmospheric temperature and precipitation conditions, and soil, vegetation and landscape changes through time[6–9]. Permafrost has warmed throughout much of the Northern Hemisphere since the 1980s, with colder permafrost sites warming most rapidly[10,11].

In northern high-latitude regions, landscape dynamics are critical for local-scale, regional-scale and global-scale biogeochemical and hydrogeomorphological processes and feedbacks[12–15]. For example, disturbance and warming of near-surface permafrost may lead to widespread terrain instability in ice-rich permafrost regions[16,17]. Such land surface changes can affect vegetation, hydrology, aquatic ecosystems, infrastructure and soil carbon dynamics[9,18,19]. Lakes and drained lake basins (DLBs) are the most prominent periglacial landforms in high-latitude lowland regions, occupying more than one-fifth of the northern circumpolar permafrost region[20]. Their dynamics profoundly affect permafrost, an important component of terrestrial and aquatic ecosystems in Arctic and boreal regions[21,22]. The environmental processes impacting and controlling the evolution of lowland permafrost on different spatial and temporal scales are intricately tied to lake dynamics with the collection, expansion and subsequent release of water through lake drainage[23,24]. The extant lake phase acts to degrade permafrost, while lake drainage processes expose fresh land surfaces for permafrost aggradation to occur, with potential for its degradation in the future[25].

These processes collectively drive dynamics in lake and drained lake basin (L-DLB) systems. Studies of L-DLB systems build off the integrated work that focused on alas basin complexes in Central Yakutia[26,27] and coastal lowland regions North America[28–30].

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Key points

- Lake formation, growth and drainage create a shifting mosaic of landforms that serve as a primary driver of landscape and ecosystem processes in Arctic and boreal lowland permafrost regions.
- The lake and drained lake basin (L-DLB) system governs geomorphic, hydrologic, ecological and human land use activities in more than 20% of the northern permafrost region.
- L-DLB systems occur in regions with both ice-rich and ice-poor permafrost terrains.
- The recent increase in the rate of L-DLB landscape dynamics in lowland permafrost regions highlights their role as a catalyst for understanding Arctic system change in a warming climate.
- Climate warming will likely increase the loss of lakes and continue to tip the landscape to one more heavily dominated by drained lake basins (DLBs).
- The rate of permafrost aggradation under DLBs will likely slow, disrupting important microtopographic controls on carbon fluxes and ecosystem processes in permafrost-region L-DLB systems. Constraining the environmental impacts of an increase in the coverage of DLBs in a warming landscape is, therefore, a critical topic for future research.

Taliks
Ground in permafrost regions that remains unfrozen year round.

Thermokarst lake
Lake that forms as a result of subsidence of the land surface due to the melting of ground ice.

Better understanding of the dynamics of the L-DLB system will improve Earth system models by better accounting for the dynamic nature of lake formation and drainage over varying spatial and temporal scales[31,32]. Future warming could inhibit permafrost aggradation in DLBs and cause persistent taliks, disrupting the trajectory of important microtopographic controls on carbon and hydrological fluxes and ecosystem processes in permafrost-region L-DLB systems. A more balanced assessment of lakes and DLBs will, therefore, provide much needed information for permafrost carbon feedback assessments[13,32] and water quality and quantity assessments[33–35]. Future land use strategy and mitigation practices, land management and risk assessments, infrastructure development and the well-being of northern socio-ecological systems in permafrost regions will need to consider potential regime shifts in the L-DLB system[36–38].

In this Review, we focus on the critical role of L-DLB processes in lowland permafrost regions of the Arctic. We present a comprehensive assessment of the geomorphic and ecological state of L-DLB districts and discuss recent observations that indicate changes in the dynamic behaviour of lakes and DLBs in these systems. We review the potential regime shifts that could alter the future state of lowland permafrost regions, including interactions between ecological, hydrological and geomorphic processes associated with L-DLB evolution and their trajectory in a warmer, wetter Arctic. We conclude by discussing the importance of understanding the coupled response of lakes and DLBs to ongoing climatic changes. More observations and Earth system model projections are needed to identify and quantify the impacts of future L-DLB dynamics in lowland Arctic permafrost regions.

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L-DLB systems

Lakes and DLBs are critical landscape elements in the Arctic system. Their initiation, growth and drainage represent the largest combined lowland permafrost-region disturbance during the Holocene. The opposing effects of lake development and lake drainage have created a mosaic of landforms that exert strong controls on geomorphic processes[39–42], hydrology[43–47], permafrost and ground ice characteristics[48–52], talik development[53–57], biogeochemical cycling and ecosystems[58–61], vegetation succession[62–65], wildlife habitat[66–68], subsistence use activities[69,70] and industrial activity[19,36,38,71]. The need to view L-DLB dynamics and patterns as part of an integrated system is highlighted in this section.

L-DLB landscape processes. The formation and drainage of lakes modulates lowland permafrost landscape dynamics. L-DLB regions occur along a continuum of ground ice conditions that control lake genesis and landscape dynamics[21,29,42,72]. The dynamics associated with lake–permafrost interactions can be categorized into primary (lake formation and permafrost degradation) and secondary (lake drainage and permafrost aggradation) stages of evolution of lowland Arctic landscapes[28,29,73,74].

Lakes in lowland permafrost regions with unconsolidated sediments form through various processes controlled by local conditions that vary with respect to palaeoenvironmental and palaeoclimate history, as well as geological and permafrost properties[41,42,75,76] (FIG. 2). Conceptually, thermokarst lake development in ice-rich permafrost terrain includes processes associated with top-down thaw of perennially frozen sediments, which promotes melting of ice wedges (or other massive ice bodies) and/or thawing of ice-rich sediments that contain layers and lenses of segregated ice[21,77]. For these thermokarst lakes, the lake basin forms in response to localized ground subsidence due to ground ice melt.

Non-thermokarst lakes are formed when the local water budget permits excess water to collect in topographic depressions within ice-poor permafrost terrain[29]. These thaw-independent basin initiation points have often been preconditioned through fluvial, mass-wasting and aeolian processes that promote the pooling of water[42]. Water accumulation within lakes in ice-poor permafrost terrain degrades the permafrost below with minimal thaw subsidence.

Despite differences in the initiation of thermokarst and non-thermokarst lakes, both these water bodies interact with the surrounding terrain through similar thermal and mechanical erosional processes. Such processes can increase the mean lateral extent of the basin by 0.1 to 1.0 m per year through degradation of the surrounding and underlying permafrost[25,78]. The lateral expansion rate of thermokarst lakes, which is determined by thermal erosion (abrasion) of ice-rich sediments, is much higher than that of lakes with a non-thermokarst origin surrounded by ice-poor permafrost[25,56]. In both lake types, the development of taliks under the lakes is a defining characteristic of the thermal interaction between surface water and permafrost[79–81].

Permafrost-region lakes tend to drain, owing to their dynamic expansion, the thaw of the surrounding sills that confine them and the dynamics of adjacent landscape features that provide a conduit for drainage[21,73,82]. Lake drainage processes in general can be linked to external factors such as changes in climate and internal factors that represent site-specific conditions, such as shore erosion and talik development[83–86]. The vulnerability of an individual lake to drain is dependent on the characteristics of the surrounding permafrost (ground ice content and distribution, ground temperature, active layer thickness), lake characteristics (bathymetry, shore

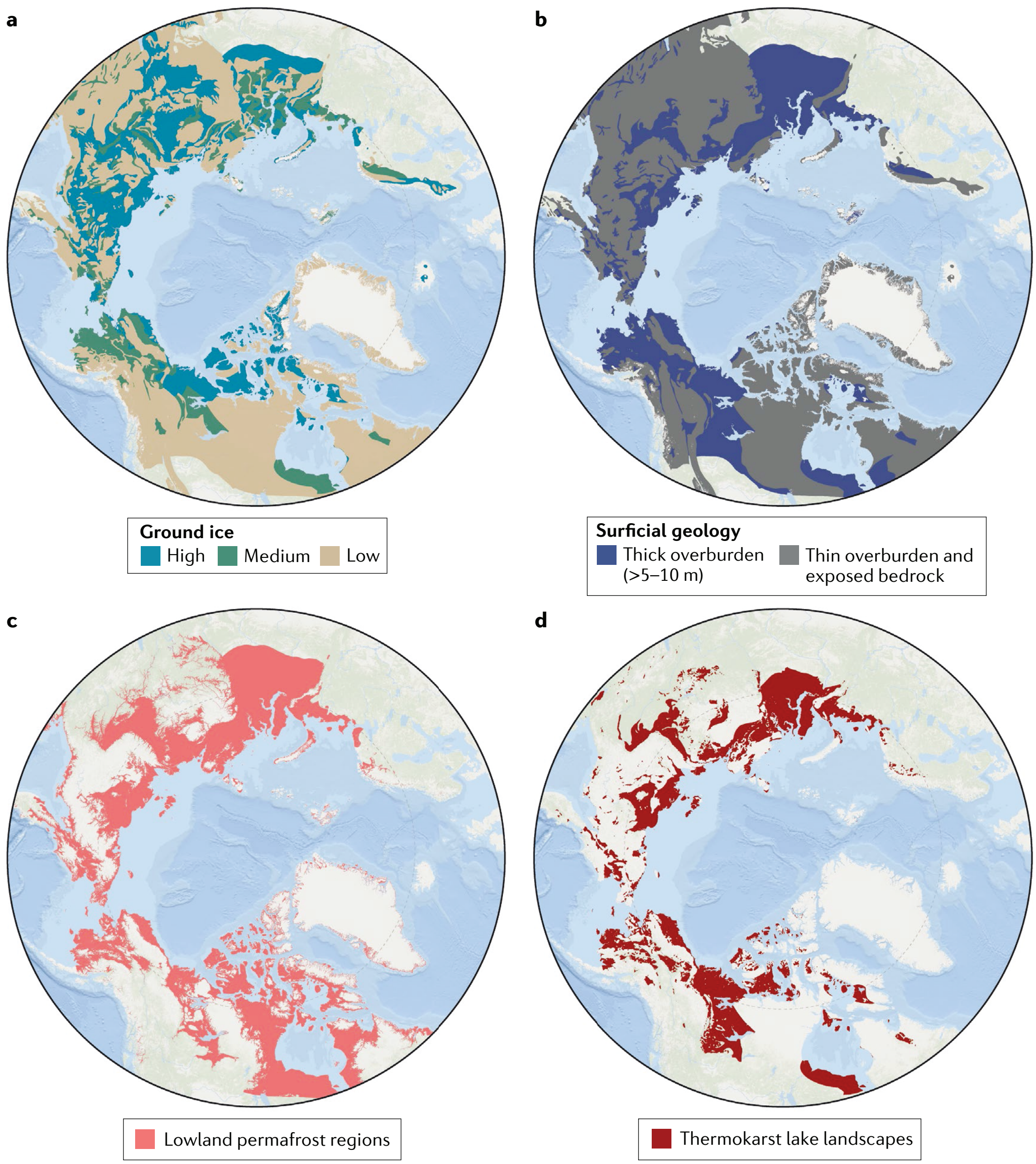

Fig. 1 | **The Arctic and boreal lowland permafrost region. a** | A portion of the northern circumpolar permafrost region showing variability in ground ice content from high (blue; >20%), to medium (green; 10–20%), to low (tan; 0–10%)[2]. **b** | A portion of the northern circumpolar permafrost region showing generalized surficial geology characterized by thick overburden cover (dark blue; including lowlands, highlands, and intramontane and intermontane depressions) and thin overburden cover and exposed bedrock (dark grey; including mountains, highlands ridges and plateaus)[2]. **c** | A portion of the lowland permafrost region (<300 m above sea level) shown in pink (derived from REF.[202]). **d** | A portion of the northern circumpolar permafrost region showing regions identified as having low, moderate, high and very high thermokarst lake coverage[20]. The figure is based upon published geospatial data sets, and we recognize that there might be misclassifications of permafrost terrain types at regional and local scales. The lake and drained lake basin system is defined as lowland permafrost regions with unconsolidated sediments with varying degrees of ground ice richness.

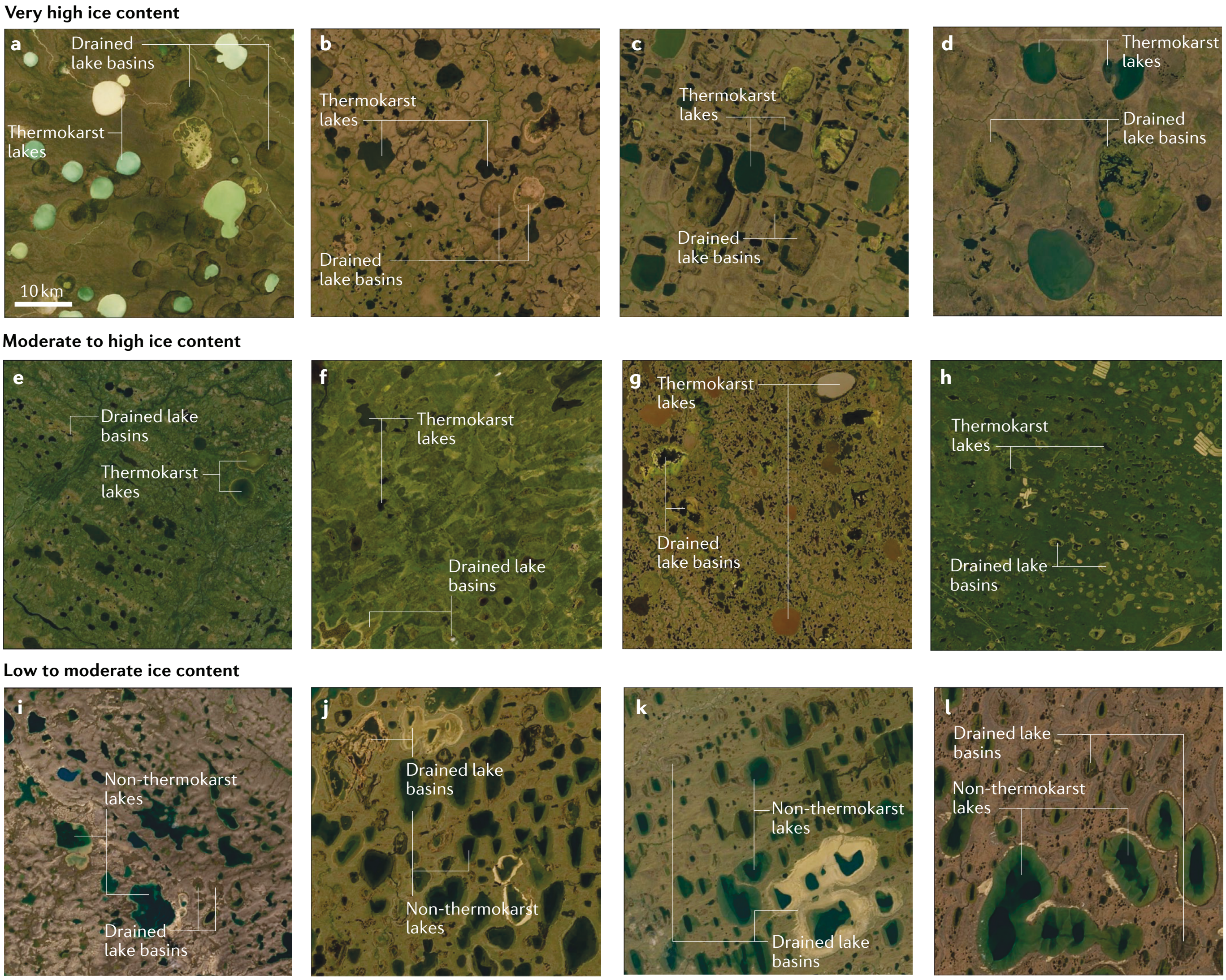

Fig. 2 | **The variability of lake and drained lake basin system districts.** Examples from Landsat satellite imagery demonstrate the variability in lake and drained lake basin districts in lowland permafrost regions with varying ice content. **a** | Koudjouak Plain, Canada. **b** | Northern Seward Peninsula, Alaska. **c** | Ayon Island lowland, Siberia. **d** | Yana-Indigirka Lowland, Siberia. **e** | Hudson Bay Lowlands, Canada. **f** | Taiga Plains, Canada. **g** | Yukon–Kuskokwim Delta, Alaska. **h** | Central Yakutian Lowlands, Siberia. **i** | Victoria Island, Canada. **j** | Western Arctic coastal plain, Canada. **k** | Arctic Coastal Plain, Alaska. **l** | Lena Delta, Siberia. Each image frame is 50 km × 50 km. Note that some basin features can also form in response to drying. Lakes and drained lake basins are the most prominent periglacial landforms in northern high-latitude lowland regions, and their dynamics impact permafrost, ecosystem and biogeochemical processes.

Bank overtopping
The process of water spilling over the lake bank, promoting lateral drainage.

Piping or tunnel flow
Drainage through open frost cracks, underground erosional channels or layers of permeable material in taliks.

Pingos
A perennial frost mound consisting of a core of massive ice, produced primarily by injection of water, and covered with soil and vegetation.

configuration, watershed and lake water balance), topography (the presence of a topographic drainage gradient and nearby landforms such as streams, river valleys, gullies, DLBs, sea coasts and other lakes), climate (air temperature, precipitation and snow cover thickness) and human activity (infrastructure development, impoundment and trenching)[21,73,82]. Common mechanisms that can lead to lake drainage include ice-wedge degradation and flow through ice-wedge troughs, headward stream erosion, snow damming, bank overtopping, river channel migration, coastal erosion, underground piping or tunnel flow, human disturbance and expansion of a lake towards a drainage gradient[21,82,85,87]. Both thermokarst and non-thermokarst lakes are prone to drainage[82], with the latter likely exhibiting more relative stability over periods of millennia, owing to their development in an ice-poor environment.

Evidence for ubiquitous permafrost-region lake drainage is found throughout the Arctic and is manifest as a palimpsest of DLB forms in lowland permafrost regions in Alaska, Canada and Siberia[28,39,88] (FIG. 2). Upon drainage, DLBs provide a fresh surface for geomorphic, ecological and hydrological succession to ensue as a series of interconnected processes[89–91]. Under a cold climate, post-drainage geomorphic processes include permafrost aggradation, ice-wedge growth, segregated ground ice formation, basin floor heave and, in some cases, the formation of pingos[50,92–94].

In the first 20 years following drainage, basins enter a new ecological state as species take advantage of the

Bølling–Allerød warming
An abrupt warm period that occurred during the final stages of the last glacial period.

initially nutrient-rich basin floors[60]. Over time, vegetation succession progresses along various pathways, depending on the local species pool and site-specific conditions[95]. Site-specific conditions are largely controlled by hydrology and post-drainage permafrost aggradation, which form a micromosaic of topographic highs and lows that can support aquatic, wet, moist and even dry tundra within basins over time[23,65,91]. The diversity of plants in any one place is largely driven by the diversity of lithology, landforms and habitats, among other factors, such as present climate, history of the flora and landscapes[64].

Collectively, across the permafrost region, these DLBs are commonly referred to as drained thaw (or thermokarst) lake basins. However, DLBs also occur frequently in regions with ice-poor permafrost[29,42,82]. One focus of this Review, and hopefully future literature, is to distinguish between drained thaw lake basins of thermokarst origin and DLBs of non-thermokarst origin, given the contrasting processes governing post-drainage succession and the future trajectory of change in permafrost-region DLBs[29,42] (FIG. 3).

L-DLB response to past climate changes. Contemporary permafrost and periglacial landscapes inherit legacies imposed by climatic variability during the late Quaternary period[96–98]. Landscape evolution and Quaternary geological history are intricately linked in permafrost terrains[41,99–101].

During glacial phases of the late Quaternary period, sediment and ground ice accumulated across large swaths of the unglaciated terrestrial Arctic (FIG. 3a). Non-glaciated permafrost regions extended throughout Eurasia and North America during the Last Glacial Maximum, from Central Europe to the Russian Plain into Siberia and through portions of lowland Alaska and north-west Canada[97,102,103]. Throughout the late Pleistocene, extensive regions were further modified by fluvial, aeolian and colluvial deposition and sediment reworking[42,98].

An abrupt increase in lake development during the deglacial period to early Holocene period was demonstrated through the application of geochronological methods (particularly radiocarbon and luminescence dating) targeting stratigraphic transitions representing the onset of ground ice degradation[40,98,104,105] (FIG. 3b). The first episode of lake formation followed Bølling–Allerød warming at 14.7 ka (REF.[98]). Much of the evidence points to the initiation of thermokarst lakes owing to increases in air temperature, and, possibly, fire frequency, that caused near-surface permafrost degradation, ground ice melt and terrain subsidence in areas with ice-rich permafrost[104,105]. The second lake initiation episode occurred during the early Holocene warm period (11.5–9.0 ka) (FIG. 3b), a relatively warm and wet period that followed the Younger Dryas. This period is thought to represent the most active period of lake formation, the so-called thermokarst wave[105], in lowland permafrost regions over the last 15 ka (REFS[98,106,107]). The increase in precipitation during the early Holocene period also likely fostered the initiation of lakes through water accumulation in antecedent depressions in thaw-stable permafrost terrain[42] (FIG. 3b).

Lake initiation in lowland permafrost regions waned after 9.0 ka before present (BP) as the system entered a new geomorphic and ecological state[98,108,109]. The early Holocene's relatively warm and wet climate ushered in modern boreal forest and tundra ecosystems with thick organic deposits, which resulted in ecosystem-driven protection of permafrost-maintaining ground thermal regimes[7]. Lakes that initiated before the early Holocene

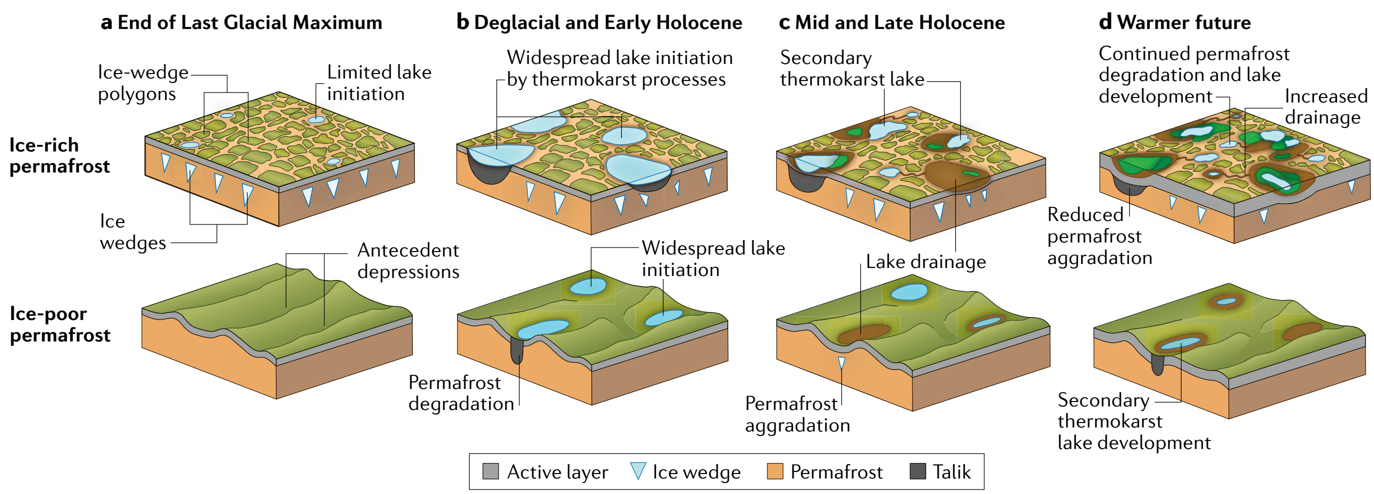

Fig. 3 | **Evolution and future trajectory of the lake and drained lake basin system.** Conceptual depiction of lake initiation and drainage in ice-rich and ice-poor permafrost lowland Arctic regions from the deglacial period, through the Holocene and in a warmer future. **a** | The end of the Last Glacial Maximum period (21–15 ka before present) landscape is underlain by cold, Pleistocene-aged permafrost that varies with respect to the presence of ground ice. **b** | During the deglacial and early Holocene periods (15–9 ka before present), widespread lake initiation occurred in both ice-rich and ice-poor permafrost lowland terrain. Lake formation in ice-rich terrain was driven by thermokarst processes and in ice-poor terrain through pooling of water in antecedent depressions. **c** | During the Mid and Late Holocene, lakes continued to form, however, lake drainage became more prevalent over time. Permafrost aggraded in recently drained basins and, in some cases, secondary thermokarst lakes formed. **d** | The warmer future will likely see a further increase in the transition from lakes to drained lake basins due to increases in landscape relief and drainage. A warmer future will also likely lead to a regime shift, whereby the aggradation of permafrost slows or ceases in freshly exposed drained lake basins. The increase in drained lake basin area and the lack of permafrost aggradation in a warming climate is a probable regime shift in the behaviour of lowland permafrost regions, with cascading effects throughout the lake and drained lake basin system[98].

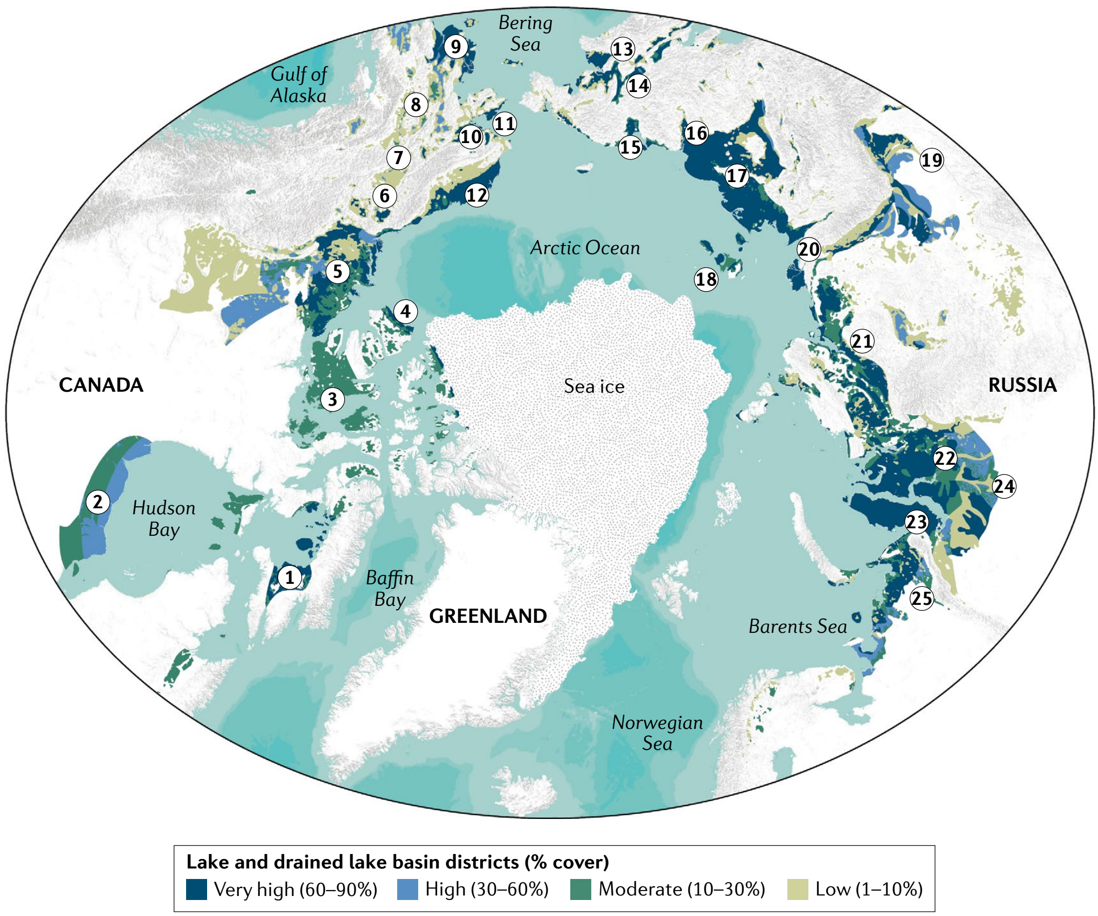

Fig. 4 | **Primary lake and drained lake basin system districts of the northern circumpolar permafrost region.** Delineation of the primary lake and drained lake basin districts based on lake and wetland-rich regions[20], the presence of unconsolidated surface sediments with varying degrees of ground ice content[2] and low-lying areas less than 300 m above sea level[202]. Percentage cover in the figure legend refers to percent of the area covered by lakes and wetlands in predefined polygon mapping units[22]. Detailed information for each numbered district is provided in TABLE 1. The figure is based upon published geospatial data sets, and we recognize that there might be misclassifications of permafrost terrain types at regional and local scales. The delineation of lake and drained lake basin districts highlights variability in this component of the Arctic system and the need to focus future efforts on the coupled response of lakes and drained lake basins to ongoing climatic changes.

ecosystem regime change also evolved through interactions with surrounding permafrost and periglacial terrain, which promoted later drainage during the mid-to-late Holocene[23,110] (FIG. 3c). The oldest known DLBs in lowland permafrost regions date to 5–8 ka BP in north-western and northern Alaska[23,107,110,111]. However, DLBs that date to 12–13 ka BP are known in north-east Siberia[99,105,112,113]. Lake drainage continued to dominate over the Holocene, with only sporadic episodes of lake initiation occurring to the present day[43,74,98]. The influence of climate change on local landscape processes, conditions and characteristics has created the modern-day palimpsest of lakes and DLBs in lowland permafrost regions in the Northern Hemisphere.

L-DLB distribution and recent dynamics. L-DLB regions represent 21% of the permafrost region area (not including the Tibetan Plateau) and 49% of lowland permafrost regions (below 300 m above sea level)[20] (FIG. 1). Typically, these regions are all considered to be dominated by thermokarst and thermokarst lake processes. Here, this distinction is refined by identifying distinct permafrost-affected lake regions based on the presence of ice-rich versus ice-poor permafrost. A classification scheme for L-DLB districts across lowland permafrost regions is further defined based on the ice content and other landscape characteristics (FIG. 4; TABLE 1). The rationale for designating the various L-DLB districts on ice content was based on the foci of previous research activity[29,42]. Regions indicative of thermokarst processes were identified due to the presence of ice-rich permafrost and an abundance of lakes and DLBs, in addition to regions or subregions with moderate to ice-poor permafrost but still with a prevalence of lakes and DLBs dominating the landscape (TABLE 1). Identification of these 25 districts highlights the variability in the L-DLB system at the circum-Arctic scale. Recognition of this dichotomy is critical for constraining future landscape evolution projections and associated feedbacks to the global climate system (FIG. 3).

Several regional mapping efforts have been made in Alaska, Canada and Siberia to quantify L-DLB cover at local to regional scales (TABLE 2). The ratio of DLBs to lakes provides a metric for the rate of landscape change that has likely occurred over the course of the Holocene to infer the long-term trajectory of various regions[28,114]. Local-scale to regional-scale studies have shown that, when combined, lakes and DLBs can occupy more than 75% of the landscape in certain regions[86,110]. In general, DLB cover is typically two to three times higher than the cover of contemporary, extant lakes (TABLE 2). Estimates of the DLB to lake ratios show that they vary from 1.1 to 16 across various L-DLB subregions (TABLE 2). The range of DLB to lake ratios helps to understand variability in permafrost ground ice conditions better and provides insights on surface process dynamics and underlying landscape characteristics[114].

Remote sensing imagery has been widely used to assess contemporary and historical L-DLB system dynamics[33,115,116]. Several local-scale to regional-scale changes in the balance of lakes and DLBs on the landscape have been assessed over the last 40–70 years[25,117]. The dominant trend is for a net loss of lake area in permafrost lowland regions and a concurrent increase in the extent of DLB cover and wetland vegetation communities[115,117,118]. The most comprehensive assessment covered 10% of the permafrost region and showed that DLB cover increased by 1.5% between 1999 and 2014 due to lake drainage[117]. However, changes in hydrology in the Kolyma Lowland in north-east Siberia[119], changes in human land use activity in Central Yakutia[43,116,120] and increases in beaver activity in north-western Alaska[121] have been shown to cause water impoundment in low-lying areas and DLBs factoring into localized increases in lake area. However, the increases in existing lake area are not rapid enough to offset the land gain through lake drainage[25,31,32]. In addition, the formation of new lakes in lowland permafrost regions remains spatially limited since the ~1990s, likely because of a highly dissected and recycled landscape and well-developed

Table 1 | **Prominent L-DLB districts in the Arctic and boreal regions**

Region	Map number	L-DLB district	Land area (km^2)	L-DLB system (% coverage)	MAGT (°C)	Ground ice content (%)
Canada	1	Koudjouak Plain	50,307	70.3	−2 to −1	High
	2	Hudson Bay Lowlands	231,738	67.3	−1 to 0	Medium
	3	Victoria Island	126,228	11.1	−7 to −6	Low to medium to high
	4	Banks Island	18,962	39.8	−11 to −10	High
	5	Canadian western Arctic coastal and Taiga plains	451,052	47.1	−7 to −2	Medium to high
	6	Old Crow Flats	12,116	48.4	−3 to −1	Medium to high
Alaska	7	Yukon Flats	38,065	27.2	−3 to −1	Medium to high
	8	Koyukuk/Innoko lowlands	43,775	37.6	−2 to 0	Medium to high
	9	Yukon–Kuskokwim Delta	57,788	86.2	−1 to 0	Medium
	10	Selawik/Kobuk lowlands	16,050	46.7	−3 to −1	Medium to high
	11	Northern Seward	8,518	60.6	−3 to −2	High
	12	Alaska North Slope	63,261	73.6	−7 to −4	Low to medium to high
Siberia	13	Anadyr lowland	39,526	59.9	−3 to −1	Medium
	14	Chaun lowland	20,250	47.1	−3 to −2	High
	15	Ayon Island lowland	15,467	54.0	−8 to −5	High
	16	Kolyma Lowland	111,978	70.4	−9 to −7	Medium to high
	17	Yana-Indigirka Lowland	309,620	67.7	−10 to −8	High
	18	New Siberian Islands	28,226	46.1	−11 to −10	Medium to high
	19	Central Yakutian Lowland	229,391	46.3	−7 to −4	Medium to high
	20	Lena Delta	20,609	72.2	−9 to −8	Medium to high
	21	Northern Siberian Lowland	325,363	55.0	−10 to −8	Low to medium to high
	22	Gydan Peninsula	257,836	67.0	−6 to −4	Medium to nigh
	23	Yamal Peninsula	113,066	77.8	−6 to −2	Medium to high
	24	West Siberian Plain	272,850	59.3	−2 to 0	Low to medium to high
	25	North Russian Plain	167,285	58.5	−3 to 0	Medium to high

Lake and drained lake basin (L-DLB) district names based on regional expert knowledge, land area and L-DLB system % cover estimated from REF.[20] by combining the area covered by lakes and wetlands in each district, mean annual ground temperature (MAGT) of near-surface permafrost from REF.[5] and percent ground ice content from REF.[2].

Table 2 | **The ratio of drained lake basins to lakes in L-DLB systems**

Region	Subregion	Lake cover (%)	DLB cover (%)	DLB to L ratio	Yedoma region?	Ref.
Siberia	Kolyma Lowland tundra zone	12	88	7.6	Yes	48
	Kolyma Lowland taiga zone, Kolyma lower reach region	20	80	4	Yes	119
	Eastern part of the Yana-Indigirka Lowland, low-lying region	18	82	4.5	Yes	119
	Eastern part of the Yana-Indigirka Lowland, mountain region	12	88	7.3	Yes	119
	Shirokostan Peninsula (Yana-Indigirka Lowland)	8	45	5.6	Yes	198
	Bykovsky Peninsula	20	46	2.3	Yes	199
	Anabar-Olenek lowland (Mamontov Klyk)	9	11	1.2	Yes	200
	Lena Delta	5	20	4	Yes and no	39
Alaska	Barrow Peninsula	22	50	2.3	No	23
	Teshekpuk Lake	23	62	2.7	No	86
	Pleistocene sand sea	18	19	1.1	No	28
	Anaktuvuk fire loess belt	2	32	16	Yes	201
	Northern Seward Peninsula	8	76	9.5	Yes	110

The higher the drained lake basin (DLB) to lake (L) ratio, the more dynamic the lake expansion and drainage rates are for the Holocene. Areas underlain by ice-rich permafrost have higher ratios than areas underlain by ice-poor permafrost. The DLB to L ratio is useful for comparing DLB occurrence for similar terrains across the circumpolar region.

erosional drainage system that is no longer conducive to widespread lake development[25,88,122].

Future L-DLB system regimes. The Arctic climate is warming, and it is affecting the pace of change in permafrost-region L-DLB systems[17,117,123] (FIG. 3d). Valuable information gleaned from palaeo-archives indicates that the boom in lake initiation that occurred at the Pleistocene to Holocene transition will likely not occur again during anthropogenic warming[98], in part, owing to the development of ecosystem protection during the Holocene[7]. Direct observations of newly forming thermokarst lakes is sparse and it appears that lake drainage will continue to dominate the L-DLB system in the future[25,117] (FIG. 3d). Advances in modelling are beginning to incorporate lake initiation and drainage dynamics into physical, empirical and Earth system models[31,32,124], although major knowledge gaps still persist in our understanding of how permafrost degradation will interact with lake dynamics.

Widespread lake drainage has been noted in north-western Alaska since 2015 and is thought to be driven by the development of terrestrial taliks as the mean annual air temperature approaches 0 °C (REFS[118,125]). As DLBs continue to form and occupy more of the lowland permafrost region landscape, their evolution will likely be disrupted as the system enters a new, warmer state that will not be favourable for permafrost aggradation (FIG. 3). Drainage of lakes in areas with continuous cold permafrost would have promoted permafrost aggradation in the freshly exposed DLBs[24,89,126,127]. However, under a warmer climate regime, the formation of permafrost on freshly exposed surfaces will slow and/or not occur at all if annual mean air temperatures exceed 0 °C. This warmer regime would permit the development of persistent within-basin taliks and inhibit the accumulation of ground ice, throwing the L-DLB system into a new landscape regime that will impact hydrology, ecosystems, carbon cycling and human activities by altering the thermal state of DLBs (FIG. 3d). However, better understanding of uncertainties associated with the L-DLB system's response to the combined effects of air temperature, precipitation, hydrologic, land cover and fire regime change are needed to develop robust projections of the future of the Arctic and boreal permafrost regions[32,55,98].

Several modelling efforts have highlighted how L-DLB systems will likely change in the future with climate change. The trajectory of the L-DLB system will likely vary as permafrost aggradation slows in freshly exposed sediments following lake drainage. Constraining the environmental impacts of an increase in the coverage of DLBs in a warming landscape is a critical topic for future research. Knowledge gaps still exist concerning the environmental factors that drive the initiation and long-term growth of permafrost-region lakes, such that reliable projections of future lake formation remain extremely limited.

Lakes and DLBs in permafrost hydrology

Interactions between permafrost, surface water, and suprapermafrost and subpermafrost groundwater are highly complex and their dynamics heavily influence surface water storage, routing, and runoff and the exchange of heat and energy in the L-DLB system[128–131].

Subsurface water. Permafrost limits sediment permeability, inhibiting water movement between surface and groundwater systems. In the continuous permafrost region, suprapermafrost groundwater is commonly perched on top of the permafrost table in the active layer and within closed subaerial and open subaqueous taliks[132]. In discontinuous permafrost regions, the lack of permafrost continuity can promote direct connections between the surface and groundwater systems, and the hydrologic dynamics of lakes can be influenced by groundwater fluxes[33,83,133]. In addition, the flow of water through hydrologically connected taliks that have developed in response to L-DLB system dynamics might also occur[134,135]. Thus, permafrost hydrological processes are conditioned by long-term legacy of permafrost characteristics such as permafrost properties, distribution, past degradation events and thickness that act to influence surface and groundwater connectivity. Short-term hydrological characteristics are subject to substantial decadal, interannual or even seasonal variability, such as ground thermal regime, active layer dynamics, and surface and soil water availability[129].

Surface–subsurface connectivity. Changes in hydrologic fluxes, induced by interactions with surrounding permafrost, have been widely studied in the L-DLB system, demonstrating the redistribution of surface water flow pathways across the landscape and potential for vertical lake drainage conduits to deep subpermafrost groundwater[83,134,135]. Changes in the surface water area of lakes have been assessed in a number of regions using remotely sensed observations, indicating a general trend in stable to increasing lake areas in the continuous permafrost zone and decreasing lake areas in the discontinuous permafrost zone[33,117,136]. However, inconsistency in observations and mediating processes within and among regions underscores the importance of site-specific permafrost and environmental conditions, the scale of measurements and the importance of quantifying complexities in feedbacks between climatologic, thermal, ecologic and hydrologic processes[129]. Better understanding the transient nature of surface and subsurface hydrologic connectivity is critical, since it plays such an important role in energy exchange, nutrient cycling and habitat connectivity in L-DLB regions[129].

Extreme drainage events. Catastrophic lake drainage events in the L-DLB system are affected by and heavily affect lowland permafrost region hydrology[37,85,137,138]. Only a few lake drainage events have been directly measured or observed in the past[73,86], so inferences related to the role of rainfall and winter snowpacks on driving permafrost-region lake drainages come from remotely sensed observations and analysis of nearby meteorological station data[82,84,118,125]. The increase in the number of lakes draining in north-western Alaska[118,125] and in the western Canadian Arctic[84] since ~2000–2010 might be attributed to an intensifying hydrological regime in certain lowland permafrost regions in the Arctic[139–142]. By contrast, more arid boreal permafrost regions are likely responding to periods of drought affecting permafrost-region lake area[136,138].

The few available observations and model estimates indicate that lake drainage events produce flood peak discharge values that are equivalent to watersheds that are two to four orders of magnitude larger than the lake basins themselves[30,86,89]. Once drained, DLBs tend to produce annual catastrophic drainages for several decades following the initial lake drainage, owing to snow damming of the DLB drainage gullies that facilitates the formation of ephemeral lakes during the peak snowmelt period and, ultimately, results in snow dam outburst floods[37]. Synchronous snow dam failure at lake outlets has been hypothesized to cause rapid and consistent flood peaks in lowland permafrost regions[143]. Since then, further observations indicate that DLBs likely play a more important role, as they have much higher storage deficits and occupy larger areas compared with lakes in most watersheds (TABLE 2).

Hydrology in permafrost regions is driven by complex processes associated with the interactions between surface water, suprapermafrost and subpermafrost groundwater systems. These complex interactions are highly dynamic in nature, being influenced by seasonal and annual variability and feedbacks associated with the thermal effect of water on permafrost. Shifts in the L-DLB system both influence and are influenced by changes in hydrology that remain an important topic of future study.

Influence of lakes and DLBs on the carbon cycle

Permafrost-region lakes and DLBs play an important role in the northern high-latitude carbon budget[144,145] (FIG. 5). In general, thermokarst lakes are seen as a positive feedback mechanism, since the lakes have a high potential to tap into the old and deep permafrost carbon pool[15,123,146], as opposed to active layer deepening that largely affects shallow and young permafrost soil carbon pools. However, recent discussions have highlighted the importance of permafrost-region lakes and DLBs for the contemporary carbon cycle and the relative role of CO_2 versus CH_4 production that factor into greenhouse gas emissions[147–150]. Below, several studies are highlighted that are seeking to address uncertainties in the role of L-DLBs on northern high-latitude carbon cycling.

Lakes and the carbon cycle. Diverse thermokarst and non-thermokarst lakes located in different terrain types in northern Alaska were found to be emitting primarily young carbon, ranging from modern to less than 3,000 years old[149]. Furthermore, the C was most likely produced within lake sediments deposited during the Holocene and CO_2 dominated the signal[148]. However, the focus of the study, performed as part of a rigorous Arctic lakes observation network, was on diffusive fluxes and important ebullition fluxes, known to emanate from deeper and older permafrost carbon in deep lake taliks[151], remain undersampled and poorly quantified for most lake types.

A similar finding was observed for what have been referred to as arid, low-relief circumpolar permafrost landscapes that include L-DLB districts such as the Yukon Flats in Alaska and other similar continental climatic settings[152]. Lakes in these prominent regions (26% of the northern permafrost region) were shown to have mineralized <1% of average terrestrial net primary production of 194 TgC per year and received little organic carbon from ancient permafrost soils based on the young age (<400 years) of radiocarbon-dated dissolved organic carbon[152]. Study of thermokarst lakes of the north-eastern European peatlands shows that moss and lichen were the dominant factors controlling the enrichment of the lake water in organic C and increasing the CO_2 concentration[153]. In Central Yakutia lakes, types and seasonality are important factors to consider[154]. Major knowledge gaps currently exist regarding the role of permafrost-region lakes in the carbon cycle. However, development of remote sensing techniques hold promise for the future[155–157].

DLBs and the carbon cycle. Compared with extant lakes, far fewer studies have been conducted on the role of DLBs in carbon cycling (FIG. 5). Following drainage, DLBs become an important environment for the accumulation of peat, the aggradation of permafrost and the establishment of a dynamic hydrologic regime controlled by snow damming of drainage outlets[23,110]. DLBs have been shown to represent an important

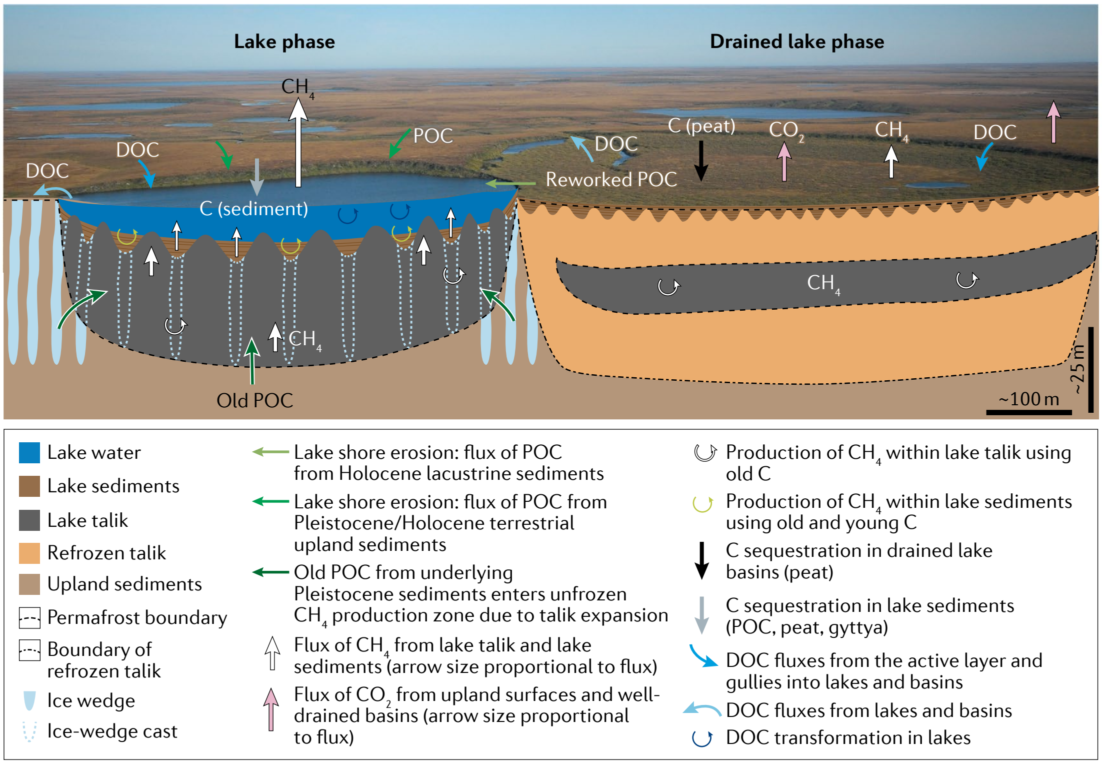

Fig. 5 | **The role of lake and drained lake basin systems in lowland permafrost carbon cycling.** Oblique aerial photograph of a thermokarst lake and drained lake basin in ice-rich permafrost on the northern Seward Peninsula, Alaska. Shown in cross section are idealized schematics of the underlying talik and permafrost configurations associated with the lake and drained lake basin phases, and key surface and subsurface carbon (C) cycling components are indicated with various arrow shades. CH_4, methane; CO_2, carbon dioxide; DOC, dissolved organic carbon; POC, particulate organic carbon. Background image courtesy of Lawrence Plug.

carbon stock in lowland permafrost regions, which, in some cases, have accumulated peat for several thousands of years[23,110]. Peat accumulation tends to initiate in the first few decades following drainage, owing to the initial establishment of highly productive plants with deep root systems, such as grasses and sedges that are dominant pioneer species, and often waterlogged soils that impede decomposition[65]. The rapid accumulation of peat slows several centuries after drainage as permafrost aggradation and vegetation succession reduce gross primary production in the DLBs[158]. In general, productivity in DLBs decreases with time since drainage. However, the development of ice wedges and the topographic controls on microtopography associated with ice-wedge polygons leads to the formation of a more heterogeneous land surface[159]. Microtopographic controls on vegetation and the lateral flow of organic matter in DLBs as they evolve following drainage to create a dynamic mosaic of carbon storage and release that deserves further study[65,159].

The general assumption is that contemporary carbon fluxes in DLBs are one to three orders of magnitude lower than that from extant lakes[32]. The lower flux of DLBs is owing to refreezing of taliks and colonization of drained basins by plants with a quick succession from fen-type wetland to bog and tundra wetlands, whose CO_2 uptake offsets emissions and CH_4 emissions are only initially high and subsequently decline[158–160]. However, the short-term and long-term carbon cycling in L-DLB systems is dynamic[161]. A DLB in central Alaska was shown to be a CO_2 source in the first 15 years following drainage, although, 30 years post-drainage, the basin became a net C sink through the establishment of vegetation and a decrease in labile compounds in the soil[162]. Over millennial timescales, following the deglacial period and early Holocene rapid expansion and associated permafrost carbon losses from L-DLB systems, they started to become a carbon sink with ongoing L-DLB maturation and climatic cooling during the mid-Holocene[112].

Major research efforts have focused on CO_2 and CH_4 emissions from permafrost-region lakes and DLBs. However, knowledge gaps remain related to the role of lakes and DLBs in the northern latitude carbon cycle. There is also a pressing need to treat the system as a shifting mosaic of landforms and disturbance patterns that affect past, present and future carbon sink and source potential.

Human livelihood and land use activity

Lakes and DLBs are key focal points for human livelihood and land use activity in the Arctic. L-DLB systems are central to the vulnerability and resilience of socio-ecological systems, defined as an analytical framework for the study of intertwined human and natural systems[163], in terrestrial and aquatic regions in the Arctic and boreal domains[164].

Lakes are commonly relied upon as a source of drinking water for Indigenous populations and for industrial activities, as surface water in permafrost regions is often the only viable source of water[165–168]. Access to a reliable source for clean drinking water is essential for northern communities. Many northern communities and villages pump water from permafrost-region lakes into holding tanks, or chip ice for household use, to supply the extended 8–9-month winter period[169].

Lakes and DLBs have been a focus of agricultural and animal husbandry activities for several hundred years across vast areas of Siberia and more locally in Alaska. In Siberia, farmers use DLBs (referred to as 'alas basins' in Yakutia) to support hay cultivation activities for horse and cattle breeding and as pastureland[170]. Productive pastureland is declining as a result of permafrost degradation occurring in alases and the surrounding landscape that is causing waterlogging of soils and subsidence[43,47,116,120], ultimately leading to less nutritious grasslands in the Sakha Republic[171]. Over time, efforts have focused on several methods for managing these DLBs to support hayfield production that includes draining, ground levelling and deforestation[70]. The largest reindeer herding region in the world is located in the West Siberian lowlands[69]. Herders use certain types of lakes in various stages of evolution as sources of drinking water in both the summer and the winter, as well as locations to drive their herds to during warm periods of the summer to seek mosquito relief. The drainage of lakes has been observed to affect migration routes and particularly camp locations, because both reindeer and herders depend on water from the lakes[172].

Several major oil and gas production fields occur in L-DLB districts in the Arctic[36,38,71]. Industrial activities make use of lakes in the wintertime by locating those that retain water below the ice in order to provide access to liquid water. Shallow lakes are also used as a source of ice chips for building ice roads and for supporting winter oil and gas exploration activities[36,173–175]. Therefore, those planning winter travel routes for exploration crews and the locations of future infrastructure[176,177] in the Arctic need to consider the dynamics of the L-DLB system[37]. A common issue in these regions, and, in particular, in areas with ice-rich permafrost, is the interactions between permafrost and infrastructure that are both costly and pose an environmental risk[177–180].

Summary and future perspectives

This Review highlights the critical role of L-DLB systems in Arctic and boreal permafrost regions. L-DLB regions occupy more than 20% of the circumpolar Northern Hemisphere permafrost region and ~50% of the area below 300 m above sea level in the Northern Hemisphere permafrost region. The balance of divergent forces associated with lake initiation and growth versus lake drainage and DLB succession occurring over millennia has dictated geomorphic processes, hydrology, permafrost and ground ice characteristics, talik development, biogeochemical cycling and ecosystems, vegetation succession, wildlife habitat, subsistence use activities and industrial activity across extensive lowland permafrost regions. Changes that have occurred over the Holocene have factored into the prevalence of DLBs relative to lakes, and have likely amplified in the twenty-first century. The increase in DLB area in a warming climate is a probable regime shift in the behaviour of lowland permafrost regions with cascading effects throughout the L-DLB system. Future warming could inhibit permafrost aggradation in DLBs and cause persistent taliks, disrupting the trajectory of important microtopographic controls on carbon and hydrological fluxes and ecosystem processes in permafrost-region L-DLB systems.

Despite 50 years of carbon cycling research on targeted aspects of the L-DLB system since the 1970s, few studies have addressed questions related to sink and source potential in a systems framework that resolves the spatial and temporal L-DLB evolution at the landscape to pan-Arctic scales[32,158,160]. Further research is needed to more fully understand the spatial and temporal dynamics of L-DLB systems and how these prominent lowland Arctic landscapes factor in the northern high-latitude carbon cycle. In addition, scaling up field observations to undersampled regions and certain waterbody types (lake versus pond) in the Arctic[154,181], limiting double-counting in scaling inventories[182] and refining discrepancies in the budgeting between top-down and bottom-up approaches[183] are essential steps forward. Future work must treat L-DLB systems as a shifting mosaic of landforms and disturbance patterns that affect past, present and future carbon sink and source potential (FIG. 5).

The mosaic created by the spatial and temporal dynamics of L-DLB systems produces habitat at various stages of succession and associated productivity that likely enhances diversity in the system[184–187]. Complex habitat mosaics are composed of diverse terrestrial and aquatic habitats that shift over time owing to ongoing landscape evolution, climate change and successional processes that can influence geomorphology and permafrost dynamics. This diversity is partly because of the portfolio effect — at any given time, each landscape tesserae in the L-DLB mosaic exists in a distinct stage of landscape evolution, harbouring its own ecological community.

As permafrost-region lakes and basins are relatively small (<10 km²), there is a relatively high diversity of landscape L-DLB stages in a local area. These diverse districts are ecological hotspots that provide essential habitat for microbes, benthic communities, terrestrial and aquatic plants, plankton, fish and birds[186]. The concept of shifting habitat mosaics has received attention in temperate and tropical systems[188–191], but rarely in the Arctic[192–194], and never solely focused on L-DLB systems. Better understanding of how various elements of the L-DLB system both respond to and offer relief from anthropogenic climate change and other stressors is needed. Habitat productivity in L-DLB systems is known to vary by landform age[60,158] and hydrological connectivity[140,195,196], but the relative proportion of shifting habitats through time and the interaction and feedbacks with wildlife populations remain largely unstudied in the Arctic.

The dynamic nature of L-DLB districts and the direct influence of climate on the major processes driving geomorphic, hydrological and ecological changes make them a prime target for future research. In addition, a focus on understanding shifting habitat mosaics and the role of L-DLBs as ecological climate refugia[197] are important to gain insight into the most biologically important regions of the Arctic. Future conservation efforts in the Arctic should prioritize the protection and study of biologically diverse L-DLB systems.

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Author contributions
B.M.J. led the synthesis and organized the international collaborative author team. All co-authors provided input on the manuscript text, figures, discussion of scientific content, regional expertise and contributed equally to all aspects of the article.

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