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Short Communication

A First Pan-Arctic Assessment of the Influence of Glaciation, Permafrost, Topography and Peatlands on Northern Hemisphere Lake Distribution

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ABSTRACT

The locations of ~200 000 large northern hemisphere lakes (sized 0.1 to 50 km^2, northwards of ~45°N latitude) are intersected with new global databases on topography, permafrost, peatlands and LGM glaciation to identify some first-order controls on lake abundance and land area fraction at the pan-Arctic scale. Of the variables examined here, glaciation history and the presence of some form of permafrost appear most important to the existence of lakes. Lake densities and area fractions average ~300–350% greater in glaciated (versus unglaciated) terrain, and ~100–170% greater in permafrost-influenced (versus permafrost-free) terrain. The presence of peatlands is associated with additional ~40–80% increases in lake density and ~10–50% increases in area fraction. On average, lakes are most abundant in glaciated, permafrost peatlands (~14.4 lakes/1000 km^2) and least abundant in unglaciated, permafrost-free terrain (~1.2 lakes/1000 km^2). Lake statistics are surprisingly similar across continuous, discontinuous and sporadic permafrost zones, decrease modestly in isolated permafrost, and drop sharply in the absence of permafrost. A simple calculation based on 'space-for-time' substitution for all glaciated/lowland terrain (~2.7×10^7 km^2, of which ~48% is currently in some state of permafrost) suggests that in a 'permafrost-free' Arctic, the number of lakes could be reduced from ~192 000 to 103 000 (−46%) and their total inundation area reduced from ~560 000 to 325 000 km^2 (−42%). A more realistic scenario of thawed discontinuous, sporadic and isolated permafrost only, with a +10% lake increase in continuous permafrost and no change in permafrost-free areas suggests reductions to ~155 000 lakes (−15%) and ~476 000 km^2 (−15%), respectively. Copyright © 2007 John Wiley & Sons, Ltd.

KEY WORDS: Arctic; lakes; LGM; glaciation; permafrost; peatlands; GIS; hydrology; global change

INTRODUCTION

Lakes, ponds and wetlands play a preeminent role in the high-latitude terrestrial hydrologic cycle, owing to their near-ubiquitous presence across low-relief landscapes northwards of ~60°N latitude (cf. Lehner and Döll, 2004, figure 2).

As the Arctic continues to show evidence of climate warming (ACIA, 2005; Hinzman *et al.,* 2005), northern lake ecosystems have come under increased scientific scrutiny. It now appears that even High Arctic lakes have already experienced biological transitions in response to rising temperatures (Michelutti *et al.,* 2005; Smol *et al.,* 2005). Other studies have used remote sensing, fieldwork and historical records to identify recent changes in the abundance and/or

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surface area of lakes and wetlands in Alaska, Canada and Eurasia (Osterkamp *et al.,* 2000; Hinkel *et al.*, 2003; Yoshikawa and Hinzman, 2003; Christensen *et al.,* 2004; Payette *et al.,* 2004; Frohn *et al.,* 2005; Smith *et al.,* 2005; Riordan *et al.,* 2006). Over longer time scales even greater changes are possible, for example major shifts in lake hydrologic balance and water levels across northern Eurasia in the mid-Holocene (e.g. MacDonald *et al*., 2004; Korhola and Weckstrom, 2005). Should broad changes in lake status occur again, there would be numerous impacts. In particular, if permafrost thaw were to cause a shift in terrestrial water storage from 'above-ground' (in lakes, wetlands and the active layer) to 'below-ground' (i.e. groundwater) storage, it would trigger profound changes to nearly every aspect of the Arctic biophysical system, including its land cover, soil carbon cycles, greenhouse gas exchange with the atmosphere, ecology and human usage. Lakes would drain and many patchy Arctic wetlands would disappear (Woo *et al*., 1992). Some possible indicators of such a shift have become evident in Russia, where draining lakes and rising river low-flows suggest an increased mobilization of groundwater systems in the late 20th century (Smith *et al*., 2005, in press).

The current spatial distribution of lakes, ponds and wetlands throughout the northern hemisphere is influenced by many factors, including substrate geology, topographic relief and drainage pattern, climate and periglacial processes. Ice sheet advance during the Last Glacial Maximum (LGM) triggered a host of glacial processes favouring a lake-rich postglacial landscape, including relief reduction, incision of bedrock depressions (particularly the Canadian Shield; Gilbert and Shaw, 1994), destruction of organized drainage, emplacement of low-permeability tills, and kettling. The presence of permafrost also promotes the persistence of lakes, by presenting a barrier to water infiltration to the sub-surface (Mackay, 1992; Woo *et al*., 1992; Rouse *et al*., 1997) and its requisite role in thaw-lake cycles (Sellmann *et al*., 1975; Billings and Peterson, 1980; Jorgenson and Osterkamp, 2005). Similarly, peats, lacustrine or glacio-marine clays, and certain organic-rich soils (e.g. gytjja) have low hydraulic conductivities, also impeding infiltration. Oligotrophic peatlands in particular have poorly organized drainage and few vascular plants, reducing transpiration losses. Over time, the accumulation of a low-permeability peatland can cause it to detach from its underlying groundwater system, further enhancing water pooling at the surface.

Clearly, a full understanding of northern lake distribution requires knowledge of many factors including precipitation, evapotranspiration, substrate permeability, permafrost properties, geology, glaciation history, peatland distribution, groundwater movement, talik depths, and periglacial processes, to name a few. Pan-Arctic datasets are currently lacking for most of these. However, recent development of global or pan-Arctic datasets on lake distribution (Lehner and Döll, 2004), permafrost (Brown *et al*., 1997), topography (GTOPO30), LGM extent (Ray and Adams, 2001), and peatlands (MacDonald *et al*., 2006) now permit a first broad-scale examination of their relative importance to lake abundance. Here, we merge the above five datasets in a straightforward geographic information system (GIS) analysis to obtain some first-order statistics on the influence of permafrost, topography, peatlands, and glaciation history on lake distribution north of 45.5°N latitude. As such, the study is similar in technical approach but far broader in geographic scope than previous studies (Sellmann *et al*., 1975; Cote and Burn, 2002; Hinkel *et al*., 2005). Because our goal is to examine long-term lake distributions in the context of static (or nearly so) environmental variables, climate datasets are specifically excluded from this study.

DATA AND METHODS

The data requirements for this analysis are the locations and surface areas of lakes; and identification of glaciated versus non-glaciated terrain, topographic lowlands, permafrost state, and peatlands (Figure 1). Shoreline polygons of lakes, rivers and wetlands are provided by the Global Lakes and Wetlands Database (GLWD) (Lehner and Döll, 2004). Global elevation data with $\sim$1 km spatial resolution and a nominal vertical accuracy of $\pm$30 m are available from the U.S. Geological Survey Global 30 Arc-Second Elevation Data Set (GTOPO30, from http://edc.usgs.gov/products/elevation/gtopo30.html). Digital maps of permafrost properties are from the Circum-Arctic Map of Permafrost and Ground-ice Conditions (Brown *et al*., 1997; revised 2001 and available from http://arcss.colorado.edu/data/ggd318.html). The extent of permanent ice during the Last Glacial Maximum (LGM) was extracted from an LGM vegetation map (Ray and Adams, 2001). This map provides a relatively conservative estimate of ice cover, with minimal LGM extent in eastern Siberia and a distinct separation between the Greenland and Canadian lobes (Figure 1b). Most recently, a first digital pan-Arctic peatland map was compiled from a variety of data sources (MacDonald *et al*., 2006).

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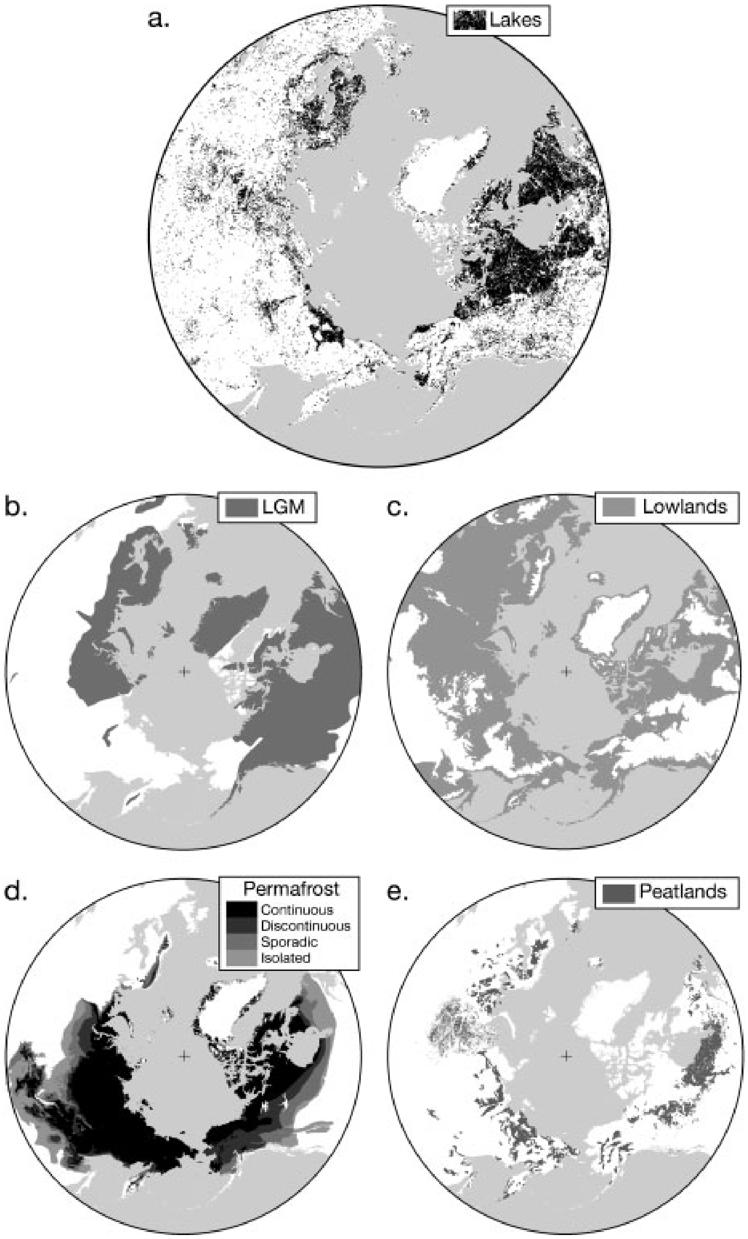

Figure 1 Data incorporated in this study are (a) lake shorelines and surface areas (Global Lakes and Wetlands Database, Lehner and Döll, 2004); (b) Last Glacial Maximum (LGM) ice extent (Ray and Adams, 2001); (c) low-elevation areas (<300 m a.s.l., GTOPO30); (d) permafrost (Brown *et al*., 1997); and (e) pan-Arctic peatlands (MacDonald *et al*., 2006).

A straightforward GIS analysis of all the above datasets was performed in ESRI ArcGIS 9.1®, using a Lambert Azimuthal Equal-Area map projection. First, a pan-Arctic land boundary base map was generated from the ESRI 1:1 000 000 World Basemap®. Since the southern limit of sub-arctic permafrost occurs at ~45.5°N latitude, all land areas northward of 45.5°N (excluding Greenland) were selected for further analysis. 'Lowland' terrain was arbitrarily defined as all land area with GTOPO30 elevations below 300 m a.s.l. Continuous, discontinuous, sporadic and isolated permafrost zones were extracted from Brown *et al.* (1997). Lake shoreline polygons were extracted from the finest-resolution GLWD data (Level 2, with surface areas between 0.1 and 50 km^2, Lehner and Doll, 2004). The LGM and peatland polygon layers were used to identify which land surfaces were glaciated during the Last Glacial Maximum, and where peatlands exist today. By intersecting the above spatial datasets in different ways, total lake counts and water surface areas were extracted, tabulated and compared among lake populations in different physical environments.

RESULTS

Excluding Greenland, the total land area northwards of ~45.5°N latitude is ~41.3 million km^2 and contains some 202 756 lakes (Table 1). The latter number is almost certainly a low underestimate, as field surveys show that even the state-of-the-art GLWD fails to capture many lakes (Frey and Smith, 2007). We identify about two-thirds of this land area (27 253 600 km^2, Table 2) as being either 'glaciated' (found within LGM boundaries) and/or 'lowland' (<300 m a.s.l., Table 1), containing 191 583 lakes or ~95% of the hemispheric (northwards of ~45.5°N) total (Table 2). Of that number, some 140 500 (~73%) occur in permafrost. The correlation between lake density (L_d) and area fraction (L_f) is strongly linear ($L_d = 0.251L_f + 0.245$, $R^2 = 0.92$).

As averaged across each zone, lake density L_d (number of lakes per 1000 km^2) in glaciated terrain is more than four times that of non-glaciated terrain (Table 1). Similarly, lake densities in permafrost, non-permafrost and lowland environments are all highest in areas that were ice-covered during the LGM (11.78, 4.58, 8.29 lakes/1000 km^2 versus 3.10, 1.23, 4.64 lakes/1000 km^2, respectively; Table 1). In terms of lake area fraction L_f (the percentage ratio of total lake area to total land area), glaciated terrain is again higher than non-glaciated terrain for every environment examined here (e.g. 3.44% versus 0.74% in permafrost, 1.50% versus 0.37% in non-permafrost, and 2.41% versus 1.19% in lowlands; Table 1). In unglaciated terrain, high values of L_d and L_f are found only in lowland environments (4.64 and 1.19%; Table 1). As measured by both sheer numbers and area-based averages (Table 1), it is clear that glaciated/lowland environments possess the greatest abundance of lakes in the northern hemisphere.

Within these glaciated/lowland environments (~2.7×10^7 km^2) a finer dissection reveals further distinctions in L_d and L_f, as a function of permafrost type and the presence of peatlands (Table 2). Highest average lake densities (11.37, 10.51, 10.96 lakes/1000 km^2) and area fractions (3.07%, 3.01%, 3.12%)

Table 1 Area-averaged lake statistics (total land and water surface areas, lake counts, lake density L_d, and percentage area fraction L_f) showing first-order influence of glaciation, permafrost and topography for all land areas north of 45.5°N (~41.3 million km^2, excluding Greenland). Note that the 'Lowlands' category redundantly includes both permafrost and non-permafrost terrain and is therefore excluded from summary ('All') calculations.

Terrain class[a]	Sub-class	Land area (km^2)	Number of lakes	Lake area (km^2)	L_d	L_f (%)
Permafrost-Influenced[b]	Glaciated[c]	9 648 000	113 679	332 100	11.78	3.44
	Unglaciated	11 167 400	34 624	82 300	3.10	0.74
	All	20 815 400	148 303	414 400	7.12	1.99
Permafrost-free	Glaciated	8 723 000	39 941	131 200	4.58	1.50
	Unglaciated	11 767 300	14 512	43 900	1.23	0.37
	All	20 490 300	54 453	175 100	2.66	0.85
Lowlands[d]	Glaciated	10 722 700	88 871	258 800	8.29	2.41
	Unglaciated	8 882 400	41 228	105 700	4.64	1.19
	All	19 605 100	130 099	364 500	6.64	1.86
All	Glaciated	18 371 000	153 620	463 300	8.36	2.52
	Unglaciated	22 934 700	49 136	126 200	2.14	0.55
	All	41 305 700	202 756	589 500	4.91	1.43

[a] All land area north of 45.5°N latitude.
[b] Continuous, discontinuous, sporadic or isolated.
[c] Within LGM maximum extent.
[d] <300 m a.s.l.
L_d = lake density per 1000 km^2 = (number of lakes/total land area) × 1000.
L_f = lake area fraction = (total lake area/total land area) × 100.

Table 2 Area-averaged lake statistics within LGM glaciated and/or lowland areas only (~27.3 million km^2, excluding Greenland), with further distinction between permafrost class and the presence or absence of peatlands.

Terrain class[a]	Sub-class	Land area (km^2)	Number of lakes	Lake area (km^2)	L_d	L_f (%)
Peatlands	Continuous	1 174 500	11 598	38 600	9.88	3.29
	Discontinuous	567 900	8188	17 300	14.42	3.05
	Sporadic	662 600	9015	23 700	13.61	3.58
	Isolated	459 000	4865	14 200	10.60	3.09
	All permafrost	2 864 000	33 666	93 800	11.76	3.28
	All non-permafrost	1 350 100	8209	22 300	6.08	1.65
	All peatlands	4 214 100	41 875	116 100	10.89	2.76
Non-peatland	Continuous	5 766 600	67 302	174 700	11.67	3.03
	Discontinuous	1 459 300	13 122	43 700	8.99	2.99
	Sporadic	1 499 900	14 685	43 700	9.79	2.91
	Isolated	1 522 000	11 725	40 300	7.70	2.65
	All permafrost	10 247 800	102 834	302 400	10.03	2.95
	All non-permafrost	12 791 700	42 874	141 700	3.35	1.11
	All peatland-free	23 039 500	145 708	444 100	6.32	1.93
All	Continuous	6 941 100	78 900	213 300	11.37	3.07
	Discontinuous	2 027 200	21 310	61 000	10.51	3.01
	Sporadic	2 162 500	23 700	67 400	10.96	3.12
	Isolated	1 981 000	16 590	54 500	8.37	2.75
	All permafrost	13 111 800	140 500	396 200	10.72	3.02
	All non-permafrost	14 141 800	51 083	164 000	3.61	1.16
	All	27 253 600	191 583	560 200	7.03	2.06

[a] Within glaciated and/or lowland terrain only.

L_d = lake density per 1000 km^2 = (number of lakes/total land area) × 1000.

L_f = lake area fraction = (total lake area/total land area) × 100.

are found in continuous, discontinuous and sporadic permafrost, respectively (Table 2). Values decline somewhat in isolated permafrost (8.37 and 2.75% for L_d and L_f, respectively) and markedly in permafrost-free terrain (3.61 and 1.16%, respectively). A further distinction between peatland and non-peatland environments finds the highest lake densities of this study in permafrost peatlands ($L_d = 14.42$ and 13.61 for discontinuous and sporadic permafrost, respectively), except in continuous permafrost where highest lake densities are found in non-peatlands ($L_d = 11.67$ versus 9.88 in peatlands). Lake area fractions are generally high across all permafrost zones ($L_f = 3.29\%$, 3.05%, 3.58%, and 3.09% for continuous, discontinuous, sporadic and isolated permafrost, respectively) with much lower values in non-permafrost ($L_f = 1.65\%$) (Table 2). In all environments, the presence of peatlands appears to increase corresponding lake area fractions at least somewhat. In the absence of permafrost, lake densities and area fractions in peatlands (6.08 and 1.65%, respectively) are substantially greater than those of non-peatlands (3.35 and 1.1%) (Table 2).

DISCUSSION AND CONCLUSION

Of the four variables examined here (LGM extent, permafrost, peatlands, and topographic relief), LGM glaciation history is the most important determinant of lake abundance, averaging more than four times that of non-glaciated terrain (Table 1). This provides quantitative support for the anecdotal notion that formerly glaciated landscapes are most favourable for lake formation. However, regardless of glacial history the presence of some form of permafrost appears to roughly double lake prevalence (Tables 1 and 2). As such, it is a substantial amplifier of lake populations in glaciated terrain with its already high lake proclivity. Lake densities and area fractions are highest in glaciated permafrost (11.78/3.44%), followed by glaciated non-permafrost (4.58/1.50%), unglaciated permafrost (3.10/0.74%) and unglaciated non-permafrost (1.23/0.37%).

With the sole exception of lake density in continuous permafrost, the presence of peatlands is associated with the highest values of both lake metrics used in this study. On average, peatlands appear to increase L_d by ~3 lakes/1000 km^2 (~40–80% greater than peat-free terrain) and increase L_f by ~0.5% (~10–50% greater than peat-free terrain) for all glaciated/lowland areas, regardless of permafrost state. Note that such increases are quite profound in permafrost-free environments with their already low lake populations: with an average density of 6.08/1000 km^2, permafrost-free peatlands support nearly twice the number of lakes as do other permafrost-free environments (Table 2).

An unexpected result is the general lack of contrast between continuous, discontinuous and sporadic permafrost, despite their decreasing permafrost fraction (i.e. continuous, 90–100%; discontinuous, 50–90%; sporadic, 10–50%; and isolated permafrost, 0–10%, Brown *et al*., 1997). Lake abundance does not appear to decline in lock-step with permafrost fraction. Instead, there is a modest decrease in isolated permafrost, with the sharpest drop by far associated with non-permafrost (Table 2). This observation is not readily explained but could indicate: (1) the estimated permafrost fractions of Brown *et al*. (1997) are poorly constrained, and/or the spatial scale of this map is too coarse to compare with lake distributions; (2) a yet unconsidered process, such as a southward trend of decreasing soil hydraulic conductivity and/or increasing regional water balance, counters the expected permafrost effect; or (3) the hydrologic impact of permafrost is non-linear, meaning that the presence of even partial permafrost contributes strongly to lake persistence. There is some basis to expect a non-linear relationship between the fractional area of permafrost and its associated hydrologic impact (subsurface water flow has a strong lateral as well as vertical component, so even scattered permafrost bodies can impede regional groundwater movement as well as thermally enhancing seasonal freezing of nearby non-permafrost), but this remains to be proven. Regardless of mechanism, the finding of similar lake statistics among different permafrost categories suggests that the simple binary distinction between 'permafrost-influenced' versus 'permafrost-free' environments (Frey and Smith, 2005) may adequately capture much of the hydrologic impact of permafrost, at least at the broad spatial scales considered here.

The spatially averaged statistics presented in Tables 1 and 2 are of little value for understanding the specific physical mechanisms underlying lake formation, and obscure many regional variations in lake density and area (e.g. the Canadian Shield with its extremely high density of lakes, Figure 1). Furthermore, they fail to distinguish the presumed effects of other important controls on lake distribution, most notably climate, soils, geology and groundwater systems. The primary contribution of this paper is therefore its relative ranking and semi-quantification of glaciation history, permafrost and peatland influences on overall northern lake distributions, as averaged over extremely large geographic areas. As such, its findings are relevant to the current debate on the possible broad-scale response of Arctic lakes and wetlands to continued climate warming and permafrost thaw (ACIA, 2005; IPCC, in press). Recent 'change-detection' studies suggest that the spatial distribution of Arctic lakes is rapidly transforming, with lake expansion in some areas (especially continuous permafrost) (Osterkamp *et al*., 2000; Jorgenson *et al*., 2001; Christensen *et al*., 2004; Payette *et al*., 2004), but shrinkage or disappearance in others (Yoshikawa and Hinzman, 2003; Stow *et al*., 2004; Riordan *et al*., 2006). Our own change-detection study of ~10 000 Siberian lakes over a large geographic area (~515 000 km^2) identified both phenomena, with a lake abundance increase of +4% in continuous permafrost but losses of −9%, −5% and −6% in discontinuous, sporadic and isolated permafrost, respectively since 1973 (Smith *et al*., 2005). Thawing permafrost was proposed as an explanation for both phenomena, i.e. causing thermokarsting and associated lake growth in continuous permafrost while enhancing infiltration to the subsurface in discontinuous, sporadic and isolated permafrost, possibly through taliks that penetrate to underlying groundwater systems (Yoshikawa and Hinzman, 2003; Burn, 2005). While the present study examines only static lake distributions, not temporal changes, the similarity in lake statistics between different permafrost zones does not support the idea of an abrupt process 'switch' along the southern limit of continuous permafrost, as implied by Smith *et al*. (2005). Instead, overall lake densities and area fractions appear relatively homogeneous across continuous, discontinuous and sporadic permafrost, decline slightly in isolated permafrost, then drop sharply in the absence of permafrost altogether.

A rough calculation of the possible impact of permafrost disappearance on northern lake populations may be made by 'substituting space for time', i.e. applying some of the spatially averaged metrics and land areas of Table 2 from non-permafrost to permafrost areas. The substitution ignores any transition period from a 'permafrost-influenced' to a 'permafrost-free' state, assumes that average lake characteristics derived from currently thawed environments may be safely applied to frozen areas elsewhere, and considers no other factors or feedbacks whatsoever. Furthermore, with the possible exception of the near-surface (Lawrence and Slater, 2005), 'complete

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disappearance' of permafrost is unlikely at anything less than millennial time scales. Given these limitations, the following should be treated as a thought exercise. Within all glaciated/lowland terrain (27 253 600 km^2, Table 2, currently containing ~95% of all lakes north of 45.5°N), if all permafrost were to disappear completely (i.e. assuming perfect conversion of all permafrost landscapes in Table 2 to their corresponding permafrost-free states, with all other factors assumed constant), lake losses would be mitigated but not precluded by the continued presence of glaciated and peatland terrains: the total number of lakes would be reduced from 191 583 to 102 844 (−46%) and total inundation area reduced from 560 200 to 324 800 km^2 (−42%). A more plausible nearer-term scenario assuming thawed discontinuous, sporadic and isolated permafrost only, a +10% lake abundance increase in continuous permafrost (more than ~2× the increase seen in Siberia since 1973; Smith *et al*., 2005) and no change in non-permafrost, would reduce the total number of lakes from 191 583 to 163 165 (−15%) and total inundation area from 560 200 to 476 100 km^2 (−15%). Such calculations, while informed, are also simplistic. More insightful understanding of northern lake distributions is anticipated as additional global datasets come online (e.g. geology, ground-ice properties) and are incorporated into modelling and field studies linking lake persistence to groundwater, permafrost and climate systems.

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