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Authors:
Joshua Culpepper[1†], Ellinor Jakobsson[2], Gesa A. Weyhenmeyer[2], Stephanie E. Hampton[3], Ulrike Obertegger[4], Kirill Shchapov[1], R. Iestyn Woolway[5], Sapna Sharma[1]

1. York University, Toronto, Ontario, Canada
2. Department of Ecology and Genetics/Limnology, Uppsala University, Uppsala, Sweden
3. Biosphere Sciences and Engineering, Carnegie Institution for Science, Pasadena, CA, USA
4. Centro Ricerca e Innovazione, Fondazione Edmund Mach, San Michele all'Adige, Italy
5. School of Ocean Sciences, Bangor University, Bangor, Anglesey, Wales

[†]**email**: joshua.abel.culpepper@gmail.com

Abstract

To date, winter limnology has focused on ice phenology, showing shorter overall ice cover. However, climate change also degrades the quality of ice. Assessments of ice quality are still rare but urgently needed, as ice thickness, transparency, and crystal structure are important for lake physics, biogeochemistry, ecosystem function, human recreation, and transportation. In this Review, we describe how climate change affects ice quality and related ecosystem services. Lake ice cover generally consists of black and white ice with black ice showing the highest bearing strength. Diminishing black ice in response to a 4 °C warmer world reduces the allowable load on ice by as much as 20,000 kilograms, implying more dangerous ice conditions for recreation and transportation. Furthermore, shifts from black to more white ice conditions can reduce the amount of light reaching the water column, limiting chlorophyll *a* by as much as 45% and altering community composition, favoring motile and mixotrophic species with potential impacts to bottom-up energy transfer. In future, developing reliable and translatable *in situ* sampling methods to assess and predict temporal and spatial variations in ice quality is much needed to guarantee safe human activities on frozen lakes.

1. Introduction

Lake ice is a critical component of the cryosphere [1]. Warming air temperatures and changing precipitation patterns have fundamentally altered the extent [2–4] and variability [5,6] of ice cover, as a direct result of anthropogenic global warming (Box 1) [7]. Over the past 150 years, ice records have revealed that lake ice forms on average 11 days later and melts 6.8 days earlier per century [8]. Late ice formation can override a later breakup within the same winter ice cover period (or vice versa), resulting in overall ice cover loss [9]. Complete ice loss in lakes is yet another result of warming air temperatures. As many as 230,400 seasonally frozen lakes are projected to no longer freeze annually by the end of the 21st Century, affecting between 394 and 656 million people [10]. Societies derive tangible benefits from ice-covered lakes [11] with millions of people using ice cover for transportation [12], fishing for sport and food [13], recreation [14], and economic benefits [15]. Moreover, ice cover loss results in warmer water temperatures [16,17], more intense thermal stratification [18], and fish habitat loss [19,20].

Despite the critical importance of lake ice to local societies and ecosystems, ice quality is rarely considered [21] even though changes in ice quality occur concomitantly with ice phenology. Ice quality describes the transparency and consistency of ice, where black ice is solid and transparent, and white ice incorporates air bubbles along with slush making it opaque and structurally weaker (Box 2) [22,23]. The quality of lake ice has immediate impacts on the safety of individuals moving on ice and the integrity of underlying ecosystems; however, limited ice quality data obscure the shift towards degraded ice conditions. As ice quality deteriorates, regulated and unregulated activities become more dangerous. In Sweden, for example, 10 individuals lost their lives in February 2021 after falling through ice consisting only of a white ice layer [21]. We can expect further drownings as ice quality conditions worsen with future climatic changes [24]. Ice quality also dictates the amount of light transmitted to the water column, which impacts under-ice water temperature, light conditions, and inverse stratification [25]. These changes in turn influence the viability of autotrophs during winter periods [26–28]. Therefore, the inability to adequately characterize contemporary ice quality limits the predictive capability of under-ice ecology across trophic levels from phytoplankton to fishes.

In this Review, we investigate the fundamental changes in lake ice quality and consequential implications for human and ecosystem health. We describe the known and projected consequences of climate warming on lake ice quality. Furthermore, we analyze available data pertaining to the safety of lake ice for various activities, such as transportation and recreation, while also investigating the potential ramifications on ecosystems that can experience reduced winter light availability due to the increased prevalence of white ice. In addition, we propose a consistent ice quality measurement method and explore the transformative potential of cutting-edge technologies, including high-frequency sensors, satellite-based observation systems, and empirical modeling techniques, in enhancing understanding of lake ice quality across different spatial and temporal dimensions.

2. Mechanisms regulating ice quality

The same forces that control ice phenology also govern ice quality, primarily air temperature, precipitation, and wind. Here, we describe the primary mechanisms that lead to the development of black and white ice.

2.1 Temperature

Air temperature is the predominant driver of the growth and decay of lake ice [29] and ice thickness [30]. Air temperature also determines ice quality, such as the thickness of black and white ice [21]. Prolonged cold air temperatures are required to form the initial ice layer, which is usually composed of black ice [31]. Once a stable layer is established, the growth of black ice depends on air temperatures cold enough to sustain the flux of energy from the water-ice interface to the atmosphere [23] (Figure 1a). The initial air temperature gradient at the period of formation dictates the grain size of ice, which impacts ice clarity [31]. A large temperature gradient can result in smaller grains as the water freezes more quickly [31]. A small temperature gradient between the atmosphere and water through the ice interface allows ice to develop slowly and results in large ice grains, which usually are more transparent. These two types of ice grains form black ice that has a higher light transparency than white ice (Figure 1a).

Temperatures above freezing can result in melt-freeze cycles that lead to white ice growth (Figure 1b,c). Specifically, initially frozen black ice undergoes melt-freeze cycles when temperatures oscillate around 0 °C [23], resulting in steadily increasing white ice growth. Continuous melting and freezing introduce gas bubbles on top of the black ice that increase white ice growth, decrease the grain size of ice, and increase opacity [31]. On top of the black ice, continuous melting and freezing introduce gas bubbles within the ice and lead to white ice with a smaller grain size and increased opacity [31].

2.2 Precipitation

The timing, amount, frequency, and in particular the type (rain or snow) of winter precipitation controls lake ice quality by limiting thermal fluxes from the water to the atmosphere [25,32]. The effect of winter precipitation on ice quality depends on the seasonal timing of snowfall or rain, lake size, and prevailing winds [33] (Figure 1). Snow has a low thermal conductivity (generally >0.3 W m^{-2} $°C^{-1}$, varying with density) [34], compared to lake ice (2.14 W m^{-2} $°C^{-1}$ at 0 °C) [23]. At the beginning of the ice cover period, the temperature gradient between the lake water and atmosphere is generally lower than later in the season. Thus, snow accumulation on the ice layer early in the season limits the growth of black ice [35]. However, thick ice also conducts less heat into the atmosphere and thus later in the season, snow accumulation can have less influence on black ice growth [35,36].

The snow cover built up by precipitation has several secondary effects of thickening the ice layer through the formation of white ice [37]. The weight of the snow layer can submerge the ice layer beneath the water surface. Subsequently, the snow layer is flooded with lake water that freezes to form white ice [23]. After accumulating, snow can undergo melt-freeze cycles, subject to fluctuations in air temperature that promote white ice growth, and rain infiltrates the pore space of snow atop ice and forms white ice when freezing [23,31]. Precipitation can be highly variable between years; therefore, ice quality conditions similarly vary [37]. When snow is artificially removed before the formation of white ice, white ice formation is effectively halted, permitting the growth of a thicker black ice layer [38].

2.3 Wind

Wind speed and direction have a strong influence on ice formation, thickness, and quality by interacting with air temperature and snow. When wind advects heat that is conducted through the ice-water interface away from the ice surface the formation of black ice is promoted [25,39]. Wind action during the ice formation period can snap thin layers of black ice. These thin layers subsequently stack into agglomerated ice and result in thick white ice layers, particularly close to the shoreline [23]. Also, turbulence during ice formation creates frazil ice and slush that can congeal and form an ice layer that incorporates air bubbles, resulting in white ice [40].

Lake ice quality is heterogeneous in space, as snow accumulation can vary on ice depending on the predominant wind direction, lake size, and land cover direction [33,41]. Wind can move snow off the ice [42] or accumulate snow non-uniformly [43]. Lakes with large fetches can experience high wind speeds that remove snow and cool the ice surface, preventing insulation from accumulating snow [23]. Larger lakes can form thicker black ice than small, sheltered lakes where snow can remain on the ice cover [43]. For example, in Lake Baikal, which has a large fetch, wind removes snow and creates black ice reaching 1 m in thickness [44,45]. Artificially removed snow cover for a lake in Wisconsin, USA, increased the proportion of black ice, and reduced the white ice proportion from a maximum of 48 cm during the control year without snow removal to 10.5 cm with snow removal [38].

3. Observed and projected changes in ice quality

Ice quality measurements are rare and collected far less frequently during winter than other limnological variables of interest, such as biogeochemical variables [46,47]. Contemporary understanding of ice quality is linked to the quantification of the under-ice light environment [48], phytoplankton abundance [49], or ice bearing strength [50]. Despite the paucity of ice quality measurements, long-term measurements that include white and/or black ice are available, albeit in geographically concentrated areas [51]. Here, we describe the contemporary understanding of lake ice quality through studies derived both from *in situ* data collection and future projections using modeling.

3.1 Observed changes

Long-term ice quality measurements are exceptionally rare but available time series data demonstrate the loss of black ice thickness [51]. In Lake Vendyurskoe in northwest Russia, both total ice thickness (-0.71 cm yr^{-1}, $p < 0.05$) and black ice thickness (-0.52 cm yr^{-1}, $p < 0.05$) declined over 25 years (1995-2020; Figure 2a). White ice did not show a significant trend during the study period. The lack of a significant trend might be due to the interannual variability of snow cover, which influences white ice development [52,53].

A long-term ecological research program in Wisconsin recorded ice thickness, black ice, and white ice measurements for 11 lakes over a 19 to 47 year period. Of these lakes, no lakes showed significant declines in ice thickness. However, one lake showed a mean decline in black ice thickness of -0.21 cm yr^{-1} and 3 lakes showed declining maximum black ice (-0.33 cm yr^{-1}). Notably, Trout Bog Lake, which significantly declined in black ice, also showed a significant increase in white ice of 0.05 cm yr^{-1}.

A well-developed lake ice sampling program in Finland demonstrated broadscale thinning of mean (-0.24 cm yr^{-1}; $p < 0.05$) and maximum (-0.29 cm yr^{-1}, $p < 0.05$, $n = 22$) ice thickness [54]. Lakes that showed decreasing ice thickness also showed significantly increasing mean (0.33 cm yr^{-1}, $p < 0.05$, $n = 4$) and maximum (0.45 cm yr^{-1}, $p < 0.05$, $n = 2$) white ice thickness. One lake showed significantly decreasing white ice thickness at a rate of -0.51 cm $^{yr-1}$. The declining total ice thickness and increasing white ice thickness imply an overall increase in the ratio of black to white ice (Figure 2b). Even though these observations coincide with overall ice loss in Finland [37] and rapidly increasing air temperatures, particularly since the 1960s [55], caution should be employed when interpreting these trends. Long-term ice quality records are few in number and are concentrated geographically (Figure 3) but emphasize the importance of collecting ice quality measurements to understand the long-term impacts of climate change on ice quality.

Remote sensing is an alternative method of ascertaining lake ice thickness, but is not capable of detecting lake ice quality at present. However, the paucity of *in situ* records complicates the assessment of lake ice thickness because validation data are limited [30]. However, ice thickness has been attained with root mean square error values of 0.12-0.41 m in Great Bear Lake and Great Slave Lake [56]. Lake ice thickness calculated using satellite altimetry methods recorded lake ice thickness in North America, Europe, and Asia with an accuracy of approximately 0.2m [30]. Despite the advancements of satellite remote sensing to detect ice thickness [57]; these methods cannot articulate the black and white ice components of the ice column.

3.2 Projected changes

Contemporary models of climate change projections all agree on the overall loss of lake ice by altered phenology and decreased ice thickness [3,58]. Only two, however, describe how future climatic changes will affect ice quality [59,60]. Projected increases of over 300% in white ice thickness across the Northern Hemisphere by mid-to-late century can be a response to future snowier conditions [59,60]. However, projections of ice thickness predominate. For example, warming air temperatures throughout the 21st Century could reduce ice thickness between 0.23

and 0.35 m [3,30]. Lake ice thickness in the Northern Hemisphere, derived from Community Earth System Model Version 2 Large Ensemble (CESM2-LE) [61], will decline by 20±7 cm compared to the 1851-1880 period (Figure 4a,b), with marked declines projected after the year 2010 (Figure 4c). Finally, compared to a preindustrial climate (1851-1880), seasonal shifts toward ice thinning with a loss of 20 cm in winter and a loss of 25 cm of ice cover during spring result from 4 °C of climate warming (Figure 4d). It is important to note that CESM2-LE does not distinguish between black and white ice; therefore, any large-scale climate model that includes the ratio of black to white ice would be an invaluable resource.

Although little direct data exist that describe how ice quality will change under future anthropogenic climate change, ice quality changes can be inferred from the projected changes of the key forcing variables: air temperature, precipitation, and wind. Warming winter air temperatures [62] can increase the number of days that vary around 0 °C, which will more frequently melt ice and snow to form slush layers that can freeze and promote white ice growth [35]. For example, even with warming of 2-3 °C, white ice contributed up to 73% of the lake ice column in Lake Abashiri, Japan [53]. In two Canadian lakes, frequent melt-freeze cycles limited black ice growth and promoted white ice growth over two anomalously warm seasons, influenced by a strong El Niño Southern Oscillation and North Atlantic Oscillation (2016 and 2017) [63]. Similarly, warm winter conditions in 2020 degraded initially black ice (70±28%) across the Northern Hemisphere to white ice (>50%) between January and March, with some lakes reaching a 100% white ice cover as early as February [21]. In addition, increasing proportions of white ice are also dependent on local precipitation regimes. For example, the western United States is tending toward a future of low-to-no snow, with declines of snow water equivalent to as much as 25% by 2050 [64]. Therefore, winters with cold temperatures could see larger proportions of black ice, but warming temperatures could still limit black ice growth. Areas with increasing snow, on the other hand, will see greater white ice proportions [37,38,63].

4. Ecosystem services

Thinner lake ice with a larger proportion of white ice creates less stable ice conditions and limits light availability during ice cover. Here, we describe the many facets of how humans are impacted by changing ice quality, including safety during transportation and recreation. We also describe the response of lake ecosystems to changing ice quality.

4.1 Transportation

Ice thickness is the most common measure of the load-bearing capacity of lake ice; however, this measure fails to consider that white ice has less load-bearing strength than black ice [65,66]. Ice with a higher density has a higher flexural strength [22], which explains the difference in bearing capacity between black and white ice. The stability of ice is not only affected by the thickness of the black and white ice layers, but also by air temperature, the thickness of the snowpack, and whether the load is static or moving [65]. Rapid drops in air temperature make the ice brittle and thus less safe due to tensions between the upper and lower surfaces of the ice cover [22,65]. The ice also loses strength if the air temperature stays above freezing degrees for 24 hours or more, or if the average daily air temperature rises above -1.1 °C [65,67]. Increasing air temperatures particularly affect white ice, which is 36 %, 21 %, and 51 % weaker than black ice at temperatures of -9.5 °C, -5.0 °C and -0.5 °C, respectively [22]. Therefore, both ice quality and atmospheric conditions must be considered when determining the safety of ice for transportation.

Due to the lack of ice quality data, ice safety guidelines for transportation can underestimate risk, as current ice measures assume that the ice consists primarily of black ice [58]. Indigenous peoples living in the James Bay region of Ontario have noted changes to winter road duration, which affects costs of necessities, livelihood, and community interconnection [68]. These individual experiences are substantiated by declines in freezing degree days in that region, where cold temperatures are required to maintain safe winter road conditions [69]. In February 2024, First

Nations communities in northern Ontario and Manitoba declared a state of emergency to address the conditions of the winter roads, which they rely on for essential goods, owing to unusually warm temperatures [70]. In the Sakha Republic in north-eastern Russia, similar concerns of increasing temperatures threaten infrastructure. Contemporary warming has not yet substantially impacted the duration of winter road travel, but can have some effect on the seasonality, through late openings or early closures [71].

Future warming scenarios indicate that transportation infrastructure will be impacted, though with regional dependencies. For example, winter road construction near James Bay in Ontario's Far North, encompassing hundreds of kilometers of winter roads, is likely to experience unstable ice conditions under future warming [68,69]. However, more inland areas will be less affected by snow and ice and possibly usable throughout the century under a warming scenario of RCP 4.5 in the CMIP5 projections [72]. The Tibbitt to Contwoyto Winter Road (TCWR), the busiest winter road in northern Canada, might experience a diminishing period of as much as 62 operational days for light vehicles at a 70 cm ice thickness threshold; however, in future scenarios, the 107 cm threshold for heavy vehicles might only be reached for a total of 4 operational days under scenario RCP 8.5 [73]. The number of days with safe ice for transport trucks, assuming an ice column of 100 % black ice, might decline by as much as 90-99 % under a 1.5 - 3 °C warmer world [58]. Given the additional ice thickness required to support the same weight in the presence of white ice, the number of safe days can be expected to decline almost entirely.

The CESM2-LE projections indicate that air temperature warming of 3 °C will decrease allowable loads on lake ice by as much as 20,000 kg throughout the Northern Hemisphere (Figure 5). The largest capacity losses will be in the Arctic regions of North America and Asia. White ice loses less overall carrying capacity with increasing temperature, but this apparent smaller loss is because the initial carrying capacity is markedly lower than that of black ice.

Therefore, many regions in lower latitudes no longer have any substantial carrying capacity (Figure 5). When viewed in comparison to maps of important roads in North America [12,73], large carrying capacities will be lost near James Bay and above Yellowknife, where critical winter infrastructure is located.

Adaptation efforts and planning are required to maintain important transportation routes, particularly as these routes can have a large economic impact. For example, the TCWR is responsible for economic activity of approximately $500 million per year (Canadian dollars) [73]. As an adaptation measure, contemporary climate warming has led to the construction of permanent roads where seasonal roads used to be viable [68]. For example, the construction of Highway 10 in Canada, which supplies transportation from Inuvik to Tuktoyaktuk, replaced a seasonal winter road, owing to concern over the continued viability of the winter road [74]. Other adaptations for the transportation of goods and services involve shifting economies to marine shipping, as the Arctic Ocean becomes increasingly ice free [75]. Improving ice safety guidelines [24,76], incorporating ice quality into models of winter road capacity, and engineering roads that promote black ice growth into climate adaptation strategies can improve critical infrastructure response[77,78].

4.3 Recreation

Ice-centric recreational activities bring revenue and cultural significance to cold-weather regions [14]. However, changing winters will result in less safe ice [58] and increasing drownings, particularly in areas with large populations of ice users and countries without strict laws on ice safety [24]. These losses are usually described in the context of ice phenology (for example, shorter seasons); however, ice quality further complicates ice safety. Ice safety will need to account for ice quality, as ice presence does not equate to safe ice use.

Ice safety thresholds based on ice thickness alone in the face of ice quality changes might need to be doubled [21]. For example, current guidelines for walking on the ice require ice to be 10 cm thick, assuming black ice, but 20 cm might be needed for safe recreation and walking on ice considering the increased prevalence of white ice [21]. The locations of outdoor winter events, such as the Olympic games, have needed to be moved as the loss of ice cover and changes to ice quality have inhibited the ability to compete [79]. Fishing tournaments in central Minnesota, USA, tend to be canceled more frequently when air temperatures are above -4 °C, indicating that ice is less likely to be safe [14]. Degrading ice conditions also increase the risk of fatal drownings. As air temperatures increase between -10 and 0 °C, winter drownings are five times higher than during winter periods with temperatures below -10 °C [24]. Furthermore, drownings tend to be highest during spring when temperatures are increasing to the point of ice melt, which also correlates with higher white ice conditions [21] (Figure 6).

Recreational activities in winter and spring months will become less safe as ice thickness declines and the ratio of white ice increases [58]. The number of days during which ice is accessible for activities such as ice fishing, skating, or festivals might decrease by as much as one week per degree rise in temperature; however, some lakes between 40 and 45 °N are projected to lose safe ice for the duration of winter [58]. The number of days for safe recreation on ice (>60 °N) will decrease by an average of 13 – 35 days in a 1.5 – 3 °C warmer world, where northeastern North America and Scandinavian countries will experience the largest increases in unsafe days [58]. Moreover, areas with the densest human populations (<60 °N) will lose between 60 - 90% of safe ice cover duration during a 1.5 - 3 °C warmer world [58]. Finally, the probability of non-fatal and fatal drownings during spring might increase, particularly in areas with high rates of winter activities, such as Canada, Latvia, and Estonia [24,76]. Therefore, the probability of drowning might increase in March and April, or even February, when warming is impacting the quality and structure of the ice cover [21,24] (Figure 6).

4.3. Lake ecology

Ice quality has a direct impact on lake ecosystems beneath the ice. A growing body of knowledge has shown the importance of ice for fostering winter algal growth, which contributes substantially to annual primary productivity [46], structures summer period ecosystems [80,81], and controls fluctuations of nutrient concentrations [47]. Ice cover periods contribute to the growth cycle of various fish species such that diminishing ice cover periods limit their growth capabilities [82] and contract their feeding habitats [20]. Much remains to be explored, however, regarding the structure and functions of ecosystems beneath ice cover. For example, ice thickness as a metric of winter severity has been used to establish distinct phytoplankton functional groups beneath ice [83]. However, those functional groups are not explored under ice quality variation, arguably the more influential variable for the under-ice environment [48]. Here, we outline perspectives on the immediate impacts to ecosystems under lake ice of changing quality.

Ice cover on lakes can both hamper and enhance conditions for life (Figure 1, Figure 7). A crucial factor for under-ice ecology is light transmission below ice. Light transmission depends on the albedo and light attenuation coefficient of the ice and snow cover, both of which are influenced by ice structure and snow depth [84,85]. Primary production under ice varies, depending on the penetration of sunlight and photosynthetically active radiation (PAR). Black ice with few bubbles transmits as much as 95% of PAR [86], where even a thin layer of ice and snow cover can still allow photosynthesis [87].

Ice cover thickness, however, does not determine the percentage of light transmission [48]. Clear ice cover can transmit nearly as much PAR as clear water. Clear ice cover on Grand Traverse Bay in Lake Michigan transmitted approximately 70-80 % of surface PAR, whereas a combination of snow cover (8.9 cm) and white ice (1.3 cm) reduced light transmission of incident PAR by approximately half (~44%) [86]. Additionally, 60% of surface light was transmitted through 40 cm of clear ice, but the percentage dropped to 20% through 30 cm of white ice [48]. Alternatively, ice cover can increase light transmission in lakes with high concentrations of suspended particles by reducing the influence of the atmosphere, which allows suspended particles to settle [88]. For example, light penetration increased by 1.5–2.2 m during the winter in turbid Lake Võrtsjärv through black ice [88]. These variations in light transmission result in differences in the ability for autotrophs to photosynthesize under ice cover, which can have larger impacts on the under-ice ecosystem.

4.3.1 Microbial communities

Microbes are likely the least explored organisms under ice, though bacteria have large and complex communities that thrive beneath ice cover [89] and moderate the balance between respiration and productivity during a period where light is a limiting factor [28]. Certain groups seem to dominate the community, for example, Verrucomicrobia [27,90,91] and Proteobacteria and Actinobacteria [27,91,92]. Bacteria perform an essential ecosystem service by breaking down dead matter, transforming dissolved carbon into biomass that can feed other organisms, and contributing to nutrient cycling, activities that continue under ice [93,94] when photosynthesis can still occur but at a diminished rate compared to the open water season [46].

Bacterial communities below ice can respond to snow thickness, indicating that light is a structuring factor for the community [27]. However, light's influence is challenging to disentangle from other factors, such as water temperature, nitrogen species, and conductivity [92]. Despite its apparent structuring capabilities, light limitation does not appear to diminish bacterial growth rates directly [95,96]. For example, the termination of an under-ice cyanobacterial bloom that followed snow cover, and therefore light limitation, increased bacterial protein production to five times its typical spring peak, suggesting that phytoplankton community dynamics factor into under-ice bacterial communities [94]. In varying lake environments, such as humic systems, bacterial production responds rapidly to the presence of phytoplankton, even under ice [95].

However, bacterial production can remain higher than phytoplankton production under ice [96]. Therefore, shifts in light abundance seem to impact the productivity of bacterial communities in relation to other factors, such as available phytoplankton biomass to break down [94,95].

The implications of these community shifts remain unclear in the face of changing ice quality that will shift the under-ice light environment. Ice presence and absence in Lake Erie altered the size of diatoms during winter, which then impacted the bacterial community [97]. The bacterial communities shifted rapidly to accommodate the variation in diatom communities from filamentous species during ice cover to smaller-sized diatoms during open water conditions [97]. Ice quality changes throughout the winter period [21] can then demonstrate under-ice cycles of bacterial succession [28] that can have impacts within the food web [97].

4.3.2 Phytoplankton communities

The effects of ice quality on phytoplankton communities are not well studied and far from being fully understood. Phytoplankton adapt to low light conditions by strategies such as denser pigment packing, altered pigment profiles, higher photosynthetic efficiency, and increased chlorophyll *a* content that maximize light absorption and photosynthetic capacity [98,99]. Furthermore, mixotrophy can be employed as a principal feeding strategy [100].

Ice quality, owing to its ability to determine mixing and light availability, influences phytoplankton communities even though mixotrophic feeding and motility can dampen this dependence [27]. The highest winter chlorophyll *a* concentrations (160-180 mg m^{-2}) [48] and phytoplankton densities [101] were observed below a transparent ice cover (Figure 7). In contrast, less than half of the concentration of chlorophyll *a* (70 mg m^{-2}) was observed under turbid ice conditions [48,102]. Artificial snow removal in a lake in Minnesota, USA, resulted in higher concentrations of chlorophyll *a*, regardless of nutrient additions (Figure 7b), implying that photoautotrophs can grow in low light conditions but rapidly respond to light availability [103] (Figure 7). Years with snow and white ice were marked by the presence of lower chlorophyll *a*

(~45% less than a year with black ice), potential mixotrophs, unicellular cyanobacteria, and Chlorophytes, whereas black ice conditions saw the presence of a photoautotrophic community (Figure 7c) [38]. However, in some eutrophic systems, snow and white ice cover benefit photoautotrophs by limiting photoinhibition that occurs when highly transparent ice allows high surface radiation into the upper water column [104].

Thermal convection under black ice conditions [105] can benefit larger groups of phytoplankton, as convection circulates nutrients [106,107] and keeps non-motile diatoms suspended in the photic zone [108–110]. Increased light transmission at snow-free sites in Lake Baikal caused convective mixing as deep as 40 m [102]. Weak or absent radiatively driven convection can lead to layered communities of motile phytoplankton [111]; however, those communities can attune to the light availability within their layer [104]. Ice thickness correlates positively with the abundance of the phytoplankton taxa Cryptomonas, Chrysoflagellates, Chrysococcus, Synura, and Chlamydomonas and negatively with the taxa Rhodomonas and Aulacoseira (Lake Müggel) [83]. These taxa represent functional groups where motile taxa performed better than non-motile taxa when ice and snow limited light penetration into the water column.

Limited light conditions and narrow light spectra penetration beneath snow and white ice layers provide a competitive advantage for phytoplankton species that absorb light in the green spectrum, indicating a possible community shift under future limited light conditions [104]. These conditions also favor motile taxa that can move nearer to the ice-water interface, or attach to the ice, where the most light will be available [112]. In addition to limited light to promote convection, taxa that rely on convection to move toward the available light can sink in a stilling atmosphere [113], which limits underwater currents [102]. Limited light is additionally likely to impact overall production with cascading impacts to the rest of the under-ice food web [114]. However, some of these impacts could be mediated by shorter ice cover periods in the future [115].

4.3.3 Higher trophic levels

The impact of ice quality on phytoplankton carries over to biomass and community composition of heterotrophic taxa, namely zooplankton, benthos, and fish [116]. For example, a phytoplankton bloom due to reduced snow and ice cover in late winter was associated with increased abundances of copepod nauplii in oligotrophic Lake Atnsjøen, Norway [117]. Similarly, the highest thickness of ice, or an ice and snow combination, showed a comparably lower abundance of zooplankton in relation to warmer systems with thinner ice and snow cover [118], as well as shifts in zooplankton community structure from calanoids (high lipid content) to cladocerans (low lipid content) [119]. Energy derived from phytoplankton during periods when the under-ice light environment is favorable for productivity benefits zooplankton, whose body mass can contain as much as 76% lipid reserves derived from phytoplankton, which enhances their ability to overwinter successfully [114].

Increasing white ice and potentially diminished primary production can alter zooplankton growth and survival beneath the ice, which is an important time of development [119]. Zooplankton abundance decreased by 51% during a year when white ice made up ~24% of the ice layer, compared to sampling during a clear ice year [120]. This change in ice quality also favors cladocerans over copepods and disrupts the energy transfer to higher trophic levels, as cladocerans are low in essential fatty acids [119].

Ice quality can also affect the links between near-surface productivity and benthic communities. Benthic organisms, such as *Diporeia*, benefit from the precipitated biomass of phytoplankton to the sediment, which contributes to the diets of benthic invertebrates [121–123] and the degradation of those organisms by bacteria [124]. In turn, benthic algae supply grazing zooplankton with sustained energy through long winters [125]. While diminished autotrophic production due to altered ice quality will limit resources to the benthos, the importance and potential impact of ice quality changes on benthic communities are unclear based on limited research that directly investigates benthic communities during the ice cover period, let alone quantify ice quality during ice cover [126].

Understanding of the impact of winter severity on fish is still developing, focusing primarily on ice phenology rather than ice quality; however, changes in photoperiod can help infer the possible shifts that diminishing ice quality can have on fishes. Desynchronization of seasonal temperatures and photoperiod cues can impact fish gonad development and egg viability [127]. Spawning at inappropriate times can increase larval mortality by spawning at harmful temperatures or by decoupling juvenile fish from the start of the spring production pulse [128]. Juvenile fish can miss early zooplankton peaks that follow phytoplankton blooms once light becomes available from reduced snow cover [129], or early snowmelt introduces nutrients to the upper water column [130]. For example, the hatching and juvenile growth of certain species, such as cisco *Coregonus albula*, historically have coincided with favorable zooplankton dynamics [131]. This asynchrony of hatching and prey availability for planktivorous fish leads to high mortality, as early life stages are more likely to deplete energy reserves during winter [128]. Therefore, the limited light availability that diminishes primary productivity [129], expected with increased white ice in warming winters, can limit food availability and fish fitness [127,128]. Shorter winter periods, even with diminished under-ice productivity, can benefit fish overall by limiting the overwintering period [82] and oxygen loss. Although, benefits can be asymmetrical, as coldwater species will lose important developmental periods with climate warming [82]. However, a more comprehensive understanding of the effects of lake ice variability on ecosystems is required [132].

6. Summary and Future Perspectives

Ice quality will directly impact the safety of human use of frozen lakes and the underlying ecosystems, lending urgency to understand the ongoing and future changes of ice quality. Based on very few available long-term ice quality time series in Finland, white ice has been increasing at a rate of 0.3 cm yr^{-1} compared to an overall ice thickness decline of 0.24 cm

yr^{-1}, implying an overall decrease in black to white ice ratios. Increasing white ice prevalence in the future will limit the timing and ability to use ice for recreation, particularly in March and April, when most cold-weather drownings occur due to unsafe ice [24]. Transportation using heavy vehicles might completely halt in a 3 °C warming world, even under scenarios of pure, black ice [58]. White ice has demonstrably altered under-ice light environments, where artificial snow removal that limited white ice development increased chlorophyll *a* concentrations by an average of 25.7 $\mu g\ L^{-1}$ in a northern Wisconsin [38]. Autotrophic productivity responses to changing ice might result in a host of bottom-up trophic interactions that could lead to losses in fitness of young-of-year fish. However, many unknowns remain, and a rapidly changing climate imposes unprecedented challenges, exposing knowledge deficits regarding how climate change alters ice quality and lake ecosystems.

In situ measurements of ice quality have varied in their purpose and are therefore sporadic, impeding aggregation of disparate ice quality sources. We recommend a standardized ice quality measurement method, based on a data collection program used by the Finnish Environment Institute [54]. Ice quality measurements should be made at a minimum of two times: once at the beginning of the season, as soon as ice is safe to walk on, and again prior to ice breakup. However, more frequent measurements, such as weekly measurements, are required for the assessment of ice safety. Four essential measurements are recommended: 1) a measure of the total ice thickness in cm; 2) a measure of black ice thickness in cm; 3) a measure of white ice thickness in cm; 4) a measure of snow and or slush thickness in cm, taken as an average of 3-5 measurements surrounding the site of ice column extraction. Additional qualitative information should be taken when possible, such as depth of white ice layers, as white ice layers can have layering with distinct colors and densities. In black ice, impurities from gas bubbles should be noted, as bubbling can happen at discrete depths and help describe the formation processes of black and white ice.

A combination of ice thickness and light data taken by high-frequency sensors provide a potential amendment to the low temporal resolution of ice quality collection through typical *in situ* methods. If ice thickness and transparency are known, by using a combination of a Shallow Water Ice Profiler (SWIP) and any number of light sensors [63], lake ice quality might be inferred based on the relationships between ice thickness and under-ice light availability [48,86]. However, light attenuation under ice is not yet fully explored. To validate the applicability of this method and its potential error, these sensor data should be validated by *in situ* ice measurements. High-frequency observations can additionally incorporate cross-sectional measurements of the entire lake surface, given the relatively low cost of sensors that can remain under the ice during winter. Incorporating transect measurements from the littoral and pelagic zones, as well as edges, are valuable to understand the risk of traveling onto ice as well as the light conditions for the littoral benthic community under ice.

Spatially diverse measurements would assist remote sensing methods that attempt to measure ice thickness on a larger spatial scale. While ice quality measurements are not yet possible using remote sensing [57,133], satellite sensors can begin to accumulate a global lake ice thickness database. For example, ice thickness was detected on 16 large lakes in North America using altimetry data from TOPEX/Poseidon and Jason-1/2/3 with approximately a 0.2 m accuracy [30]. Aggregating multiple satellite sensors can improve synthetic aperture radar (SAR) image density to estimate ice quality, for example through the use of satellite constellation missions such as Sentinel-1 A/B and Radarsat Constellation Mission [57] and the development of radiative transfer models such as the snow microwave radiative transfer model (SMRT) [134,135]. Tools such as SAR and models like the SMRT in conjunction with lake ice models can help predict the presence of non-black ice layers as well as how those layers change throughout the season [134].

Modeling offers an additional avenue to provide ice quality assessment, and importantly, forecasting. Models such as DYRESM-WQ-I account for layers of black ice, white ice, and snow cover [136]. The attempts to account for white ice have underpredicted the thickness of the layer and overpredicted the thickness of black ice [137]. This underprediction might result from the DYRESM-WQ-I model isolating the formation of white ice to the intrusion of lake water as a result of ice and snow weight overcoming ice buoyancy [136,137]. A tuning parameter, such as the snow compression rate parameter, might assist this prediction of white ice development [53]. Pairing models that predict black and white ice layers with models that account for spatial heterogeneity of ice thickness, for example the Aquatic Ecosystem Model, AEM3D, can help predict complex heterogeneous patterns of ice cover along a lake surface [138]. Ice models that better predict lake ice quality can further contextualize active and passive remote sensing and safety protocols for lakes that commonly hold recreation or transportation activities.

Satellite sensors and models are not easily accessible or interpretable to community members and stakeholders, but tools that project ice conditions on lakes could prevent drownings and transportation issues. Therefore, the combination of *in situ*, remote sensing, and modeling will likely be necessary to predict real-time ice thickness and ice quality for the purposes of ice safety, similar to weather advisories, which would greatly benefit freshwater management during winter. For example, models might have large errors that cannot be corrected during formation and breakup, when lake ice is most dangerous. Remote sensing data could help correct ice quality models when ice is too dangerous to collect *in situ* samples. Likewise, consistent ice quality observations during a safe ice cover period can help adjust models to predict when ice cover will begin to become unsafe, which can be much earlier in the season during warm years and years with high white ice cover [21]. As it stands, data on ice quality are severely lacking, inhibiting the broadscale application of methods to help prevent drownings and transportation failures as well as under-ice impacts on aquatic ecosystems in a warming world.

Figure Captions

Figure 1: Impacts on ice quality in a warming climate.

Changes to lake ice quality with changing meteorological forcing. Panels A to C represent a gradient of increasing liquid precipitation, less solid precipitation, increasing air temperatures, and decreasing light transparency of ice. The increasing white to black ice ratio that accompanies increasing temperature and changing precipitation patterns influences ecosystem services. Black ice is more stable for transportation and recreation than white ice. Black ice transmits more light than does white ice, leading to changes in under-ice light availability for photosynthesis, which alters phytoplankton community composition. Figure created with BioRender.com.

Figure 2: Observed ice quality trends.

Time series plot of ice thickness, black ice, and white ice (panel A) in Lake Vendyurskoe, Russia[51]. Variability in trends for total ice thickness and white ice thickness (panel B) for Finnish Lakes based on >30-year time-series. Lake Vendyurskoe shows significant declines in total ice thickness (0.71 cm yr^{-1}) and black ice thickness (0.52 cm yr^{-1}), but no discernable trend in white ice. Nine Finnish Lakes show significant trends in both total ice thickness and white ice thickness, where total ice thickness declines at a mean rate of 0.24 cm yr^{-1} and white ice increases in 8 of the 9 lakes at a mean rate of 0.3 cm yr^{-1}. Data for the Finnish lakes are publicly available from the Finnish Environment Institute [54].

Figure 3: Global distribution of ice quality measurements.

Ice quality measurements across the Northern Hemisphere (panel A). Subsequent maps show that published data primarily derive from Europe (panel B) and North America (panel C). Individual points represent a lake with ice quality measurements (such as total ice thickness, black ice, and white ice) and these points are colored by the percent maximum thickness of white ice during the winter of 2021, when the Ice Blitz project took place [21]. Furthermore, points are either presented as a circle for lakes with only a single year of data (at least one year of black and white ice thickness measurements was required to be included), a square for <10 years of data, or a triangle for lakes with >10 years of data. The lakes are primarily focused in Europe (taken from published, primary literature with a focus on Finland where ice quality measures are part of the national monitoring program [54]), while North American time series come exclusively from the North Temperate Lakes dataset [139].

Figure 4: Projected changes to ice thickness as a proxy for ice quality.

Average ice thickness in the Northern Hemisphere for a warming scenario of 1 °C (panel A) and 2 °C (panel B). Ice thickness declines are particularly prominent in latitudes north of 60° with decreases >30 cm. The trend of ice thickness changes for past and projected years (panel C); the shaded area represents the standard deviation of ice thickness changes. The yellow and orange circles represent 1 °C and 2 °C warming, respectively. (Panel D) Ice thickness declines at plus 1 °C, 2 °C, and 4 °C compared to a historical average for both the winter and spring, which are typical times when ice cover is used for transportation and recreation. Projections derived from the Community Earth System Model Version 2 (CESM2-LE) [61].

Figure 5: Changes to allowable load on lake ice under a warming climate and different ice quality ratios.

Change to the allowable load on lake ice. Each panel represents a change both in warming and ice quality (100% black ice, 50% black ice, and 100% white ice). The allowable load declines most in Arctic regions where black ice declines, leading to a loss in the allowable load of as much as 20,000 kg. The scenario with 100% white ice has a lower loss in load-bearing capacity because it can hold less load from the beginning. Projections derived from the Community Earth System Model Version 2 (CESM2-LE) in conjunction with an updated equation for bearing capacity [21,65].

Figure 6: Monthly statistics of drowning through lake ice.

Monthly average drownings through lake ice during available years [24]. Each point within the box and whisker plots depicts the average drowning in people per 10,000 inhabitants in countries where data were available. April has the highest average drownings across countries, with a high of 359 drownings per 10,000 people in Estonia.

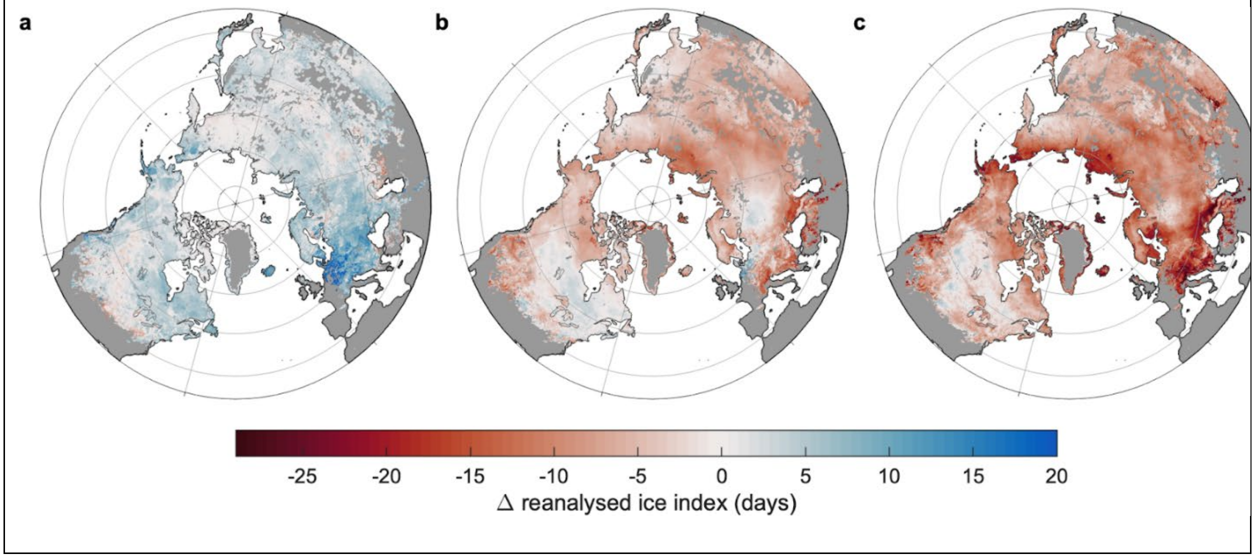
Figure 7: Differences in primary production between snow-covered and snow-cleared ice.

Metrics of productivity, both net primary productivity (NPP) (panel A) and chlorophyll *a* (panel B and C), in research where lakes were experimentally cleared of snow[38,103,104]. Clearing lakes from snow increases productivity metrics. In the late snow removal (panel C), the lake ice had time to develop into white ice, owing to a late start to the season from unsafe conditions[38].

Boxes

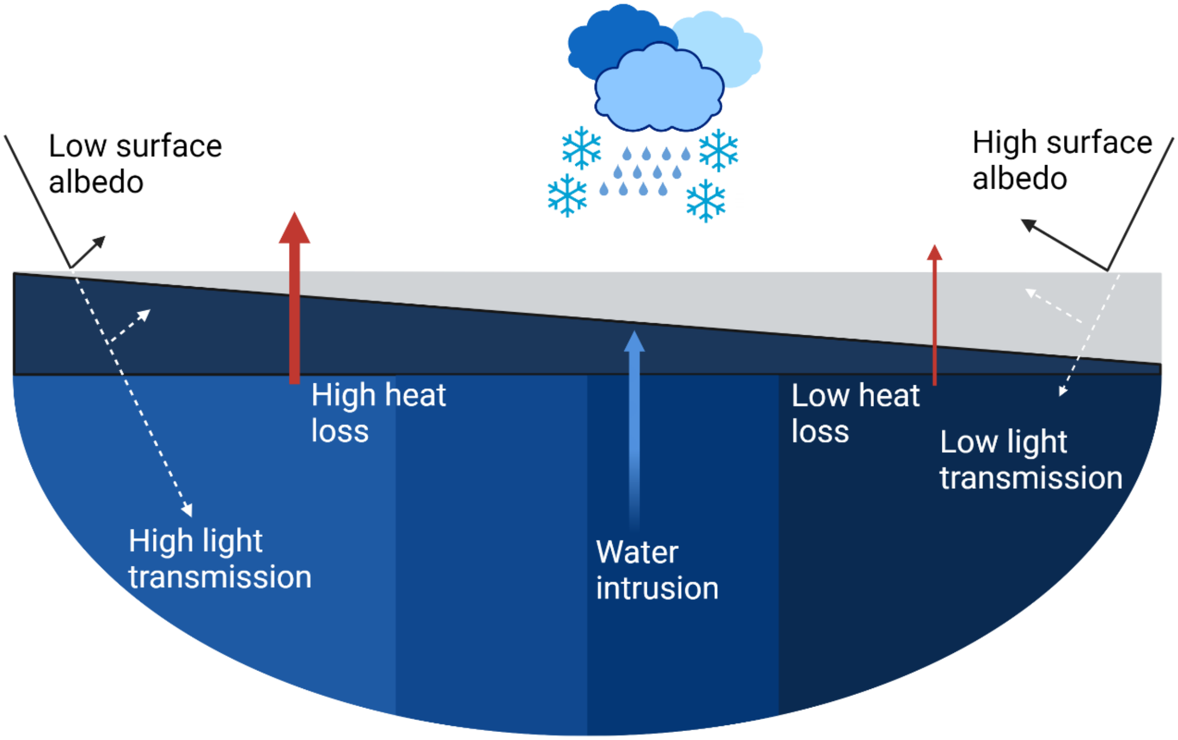
Box 1: Changes to lake ice phenology and duration

Lake ice cover is considered an Essential Climate Variable [1] and a sentinel of climate change [140]. Lake ice records are some of the oldest observations of climate, extending long before the start of the Industrial Revolution [115]. The most common metric of ice cover is the timing of ice formation and breakup (often referred to as ice phenology). These annual events have been recorded across the Northern Hemisphere [115,141]. A large number of studies have calculated trends in ice phenology and overwhelmingly found that generally, lakes freeze later and thaw earlier, with shorter duration of ice cover [9]. More specifically, *in situ* observations of lake ice records have revealed that ice duration is 17 days per century shorter over the last 100-200 years, with rates of ice loss six times faster in the past 25 years [8]. Lake ice responds directly to warming air temperatures with ice cover tending to decrease by 9.7 days per degree Celsius increase [7]. As illustrated in the figure below, ice formation is approximately 3 days later, ice breakup is 5 days earlier, and ice duration is 9 days shorter on average across the Northern Hemisphere between 1981-2019 [7].



Future projections of ice cover project widespread loss of ice cover across the Northern Hemisphere this century. Ice formation is projected to occur 20 ± 8 days later, ice breakup is predicted to be 20 ± 7 days earlier, and ice duration is predicted to last 38 ± 11 days shorter by the end of the century [3]. Moreover, ice thickness is projected to decline by 0.18 ± 0.1 m [30]. An areal increase of up to 11.7% ± 1.6% of lakes are projected to become intermittent by 2100 [3] and almost 5,700 lakes could permanently lose ice cover by the end of the century based on the RCP 8.5 greenhouse gas emissions scenario [142].

Box 2: Black and white ice formation process



Ice quality describes the ratio of black to white ice that forms due to different physical drivers. Black and white ice have different qualities, such as bearing capacity and opacity.

Black ice (also called clear ice or congelation ice) requires cold and calm conditions such that an ice layer forms undisturbed on a lake. Black ice appears transparent because nearly as much light passes through it as through liquid water. Black ice, however, can be more transparent than water, as it tends to have a much smaller concentration of dissolved or suspended matter than water or white ice [23]. Black ice forms beneath the first thin ice layer and grows parallel to the heat flux from the water column. The growth of black ice continues until the conduction of latent heat from ice formation at the ice-water interface is greater than the heat flux into the water [23].

Snowfall can slow or even halt the formation of black ice because snow's low thermal conductivity slows the release of latent heat from ice formation through snow [23,143]. Slowed heat loss keeps crystal size large [23,31], maintaining the transparency of black ice [23]; however, snowfall also results in formation of white ice (also called snow ice or superimposed ice), which has small, randomly oriented crystals and impurities that create opaque ice. In general, white ice forms either through the melting and refreezing of snow, for example during diel freezing cycles in spring, or when enough snow accumulates on the ice such that the ice cover sinks and lake water fills the pores space in the snowpack, eventually refreezing [144–146]. White ice also forms when rain infiltrates pore space in the snow layer to form slush, which subsequently freezes as a combination of white ice layers and slush [23,25,147]. In dry places or areas where extremely cold temperatures prevent adhesion between the snow and the ice surface, white ice forms less frequently [23].

Figure created with BioRender.com.

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