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Consequences of lake and river ice loss on cultural ecosystem services

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Scientific Significance Statement

Inland lake and river ice are underappreciated resources threatened by climate change. Over the past 150 years, seasonal ice cover duration on Northern Hemisphere lakes and rivers has been decreasing. Ice-cover loss affects ecosystem services in various ways, but comprehensive studies evaluating the interplay between society and ice-covered lakes and rivers are lacking. For the first time, we provide quantitative evidence of the diverse ways that the loss of inland ice may reduce cultural ecosystem services.

Abstract

People extensively use lakes and rivers covered by seasonal ice. Although ice cover duration has been declining over the past 150 years for Northern Hemisphere freshwaters, we know relatively little about how ice loss directly affects humans. Here, we synthesize the cultural ecosystem services (i.e., services that provide intangible or nonmaterial benefits) and associated benefits supported by inland ice. We also provide, for the first time, empirical examples that give quantitative evidence for a winter warming effect on a wide range of ice-related cultural ecosystem services and benefits. We show that in recent decades, warmer air temperatures delayed the opening date of winter ice roads and led to cancellations of spiritual ceremonies, outdoor ice skating races, and ice fishing tournaments. Additionally, our synthesis effort suggests unexploited data sets that allow for the use of integrative approaches to evaluate the interplay between inland ice loss and society.

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With the majority of the world's lakes located at higher latitudes (>45°N) in the Northern Hemisphere (Verpoorter et al. 2014), seasonal ice cover is a common phenomenon (Denfeld et al. 2018). As a result of climate change, shorter ice duration or incomplete ice cover are becoming more common around the world (Magnuson et al. 2000; Benson et al. 2012; Sharma et al. 2019). Projected trends for air temperature and snow cover in the Northern Hemisphere suggest that seasonal ice cover duration will continue to decline (Shuter et al. 2013; Yao et al. 2014; Magee and Wu 2017; Hewitt et al. 2018; Sharma et al. 2019).

Such losses in lake and river ice do not occur without reducing the uses of ice cover by people. However, it appears that the cultural ecosystem services and benefits that ice

provides are often underacknowledged (Magnuson and Lathrop 2014). Cultural ecosystem services are defined by the Millennium Ecosystem Assessment as “the nonmaterial benefits people obtain from ecosystems through spiritual enrichment, cognitive development, reflection, recreation, and aesthetic experience, including, e.g., knowledge systems, social relations, and aesthetic values” (Millennium Ecosystem Assessment 2005). More recently, cultural ecosystem services have been defined as “ecosystems’ contribution to the non-material benefits (e.g., experiences, capabilities) that people derive from human-ecological relations” (Chan et al. 2011). Seasonal lake and river ice serve as natural capital (i.e., living and nonliving parts of ecosystems contributing to the generation of goods and services of value for people [Guerry et al. 2015]) that supports cultural ecosystem services, associated benefits, and human well-being in many ways (Fig. 1).

The effects of reduced inland ice on cultural ecosystem services warrant attention because 14,800 lakes along the southern limit of ice-covered lakes have already begun to experience intermittent ice-free years (Sharma et al. 2019). In addition, climate change-related ice losses are expected to negatively affect 35,000–230,000 lakes, in 41–50 countries, and up to as many as 654 million people as annual air temperatures are projected to increase (Sharma et al. 2019). Even air temperature increases as small as 1°C may influence over 100 million people living near seasonally ice-covered lakes.

Several authors have suggested that there will be a loss of cultural ecosystem services as seasonal lake and river ice cover declines (Dawson and Scott 2010; Prowse et al. 2011; Magnuson and Lathrop 2014; Jansson et al. 2015), but a review of the literature found few empirical studies. Of these, some have used observational data to demonstrate that

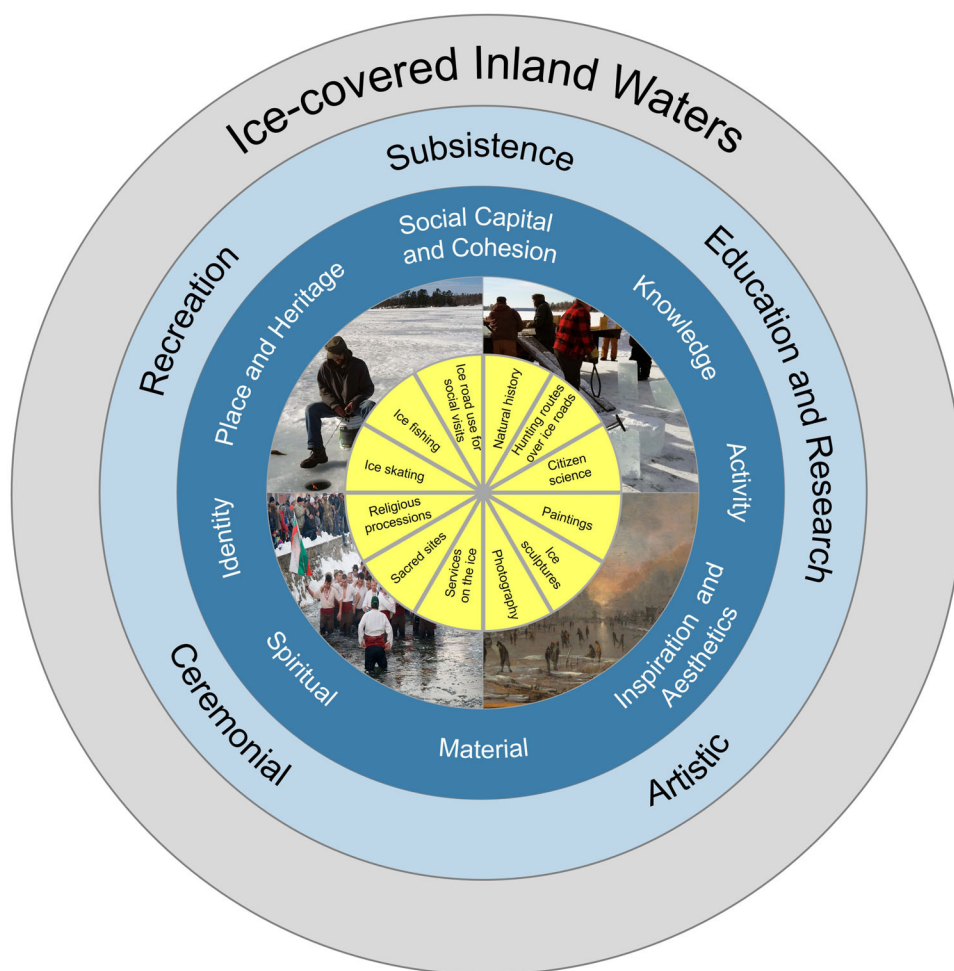


Fig. 1. Ice-covered inland waters contribute to people and a good quality of life in many ways. Here, we classify ice as natural capital (gray circle) providing five categories of cultural ecosystem services (light blue circle) and associated benefits (dark blue circle). Specific examples of activities on the ice are shown in the inner circle (yellow). Photo credits: (1) ice fishing on Minnesota lake, Lesley Knoll; (2) traditional ice harvesting demonstration on Minnesota lake, Lesley Knoll; (3) Sports on a Frozen River by Aert van der Neer (ca. 1660), Metropolitan Museum of Art, New York; and (4) celebrating the Epiphany in Kalofer, Bulgaria, Balkanregion [CC BY-SA 3.0 <https://creativecommons.org/licenses/by-sa/3.0>], from Wikimedia Commons.

warming winters are negatively impacting outdoor ice skating across the world (Visser and Petersen 2009; Brammer et al. 2015; Robertson et al. 2015; Liu et al. 2017). An empirical approach also has been used to show the influence of climate change on winter ice roads. Ice roads that traverse ice-covered water bodies are not directly a cultural ecosystem service, but they enable essential services and benefits such as allowing movement and social connections for isolated communities. As such, there is increasing interest in this topic with a handful of quantitative studies examining the negative influence of warming winters on ice roads (Knowland et al. 2010; Kiani et al. 2018). In addition, some research has been devoted to subsistence activities that reflect cultural identity, sense of place, and traditional knowledge. A recent study of the Tanana River in the interior of Alaska combined remote sensing of river freeze and breakup dates with local observations on travel safety to show a shorter season for subsistence activities via river ice (Brown et al. 2018). Although these empirical studies provide convincing examples of ways that lake and river ice loss affect cultural ecosystem services, additional research and synthesis is needed to inform future predictions.

To better understand the interplay between ice-covered inland waters and society we: (1) synthesized major cultural ecosystem services and benefits provided by lake and river ice cover across the world, (2) compiled and analyzed data to present new empirical examples of the consequences of lake and river ice loss on cultural ecosystem services, and (3) identified potential research directions for the future. We examined spiritual traditions by the Shinto religion in Japan and the Catholic religion in Germany and Switzerland; outdoor ice skating races in Sweden; ice fishing tournaments in the U.S.A.; and winter ice roads used by indigenous communities and the private sector in Canada. Our empirical examples considered ice as natural capital and examined the influence of climate variability (i.e., warm winters vs. cool winters) on diverse benefits and activities. With the exception of the spiritual examples, our data are not of the time scale to assess climate change, but our results have implications for climate change because long-term trends in many parts of the world show declining ice cover (Magnuson et al. 2000; Sharma et al. 2019). Although our examples are quantitative, we note that many human uses related to lake and river ice, such as a loss of sense of place, are more difficult to evaluate empirically and to assign a dollar value (Chan et al. 2012).

Cultural ecosystem services and benefits provided by inland ice: A framework

Conceptual framework

When the Millennium Ecosystem Assessment was published in 2005, cultural ecosystem services were the least developed ecosystem service category (Costanza et al. 2017). Since then, there has been a wide range of approaches to define cultural ecosystem services, place them in frameworks, and to

put a value on them; however, a unified approach has not yet been adopted (Costanza et al. 2017). We used the ecosystem service approach for the basis of our conceptual framework (Fig. 1) because there is a long history of related research in this developing field (Costanza et al. 2017). There are additional ways to frame cultural ecosystem services, such as that suggested by the ongoing work from the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. They aim to broaden how cultural ecosystem services are defined by placing them in the contexts of nature, nature's contribution to people, and their potential for influencing quality of life (Díaz et al. 2018).

Our conceptual framework was adapted from a previously developed hierarchical classification (Chan et al. 2011). We considered ice as natural capital that supports five categories of cultural ecosystem services: ceremonial, artistic, education and research, outdoor recreation, and subsistence (Fig. 1). We then recognized several categories of benefits derived from those services: aesthetic, place and heritage, activity, spiritual, inspiration, knowledge, social capital and cohesion, identity, and material (Fig. 1). Although Chan et al. (2011) describe more benefits, we selected these because of their relation to lake and river ice. The five cultural ecosystem service categories are neither independent from each other nor from other ecosystem services (i.e., provisioning, regulating, and supporting ecosystem services). Similarly, each cultural ecosystem service category may have multiple benefits. For example, outdoor recreation can be related to activity, place and heritage, identity, social capital and cohesion, and knowledge benefits. In some cases, like fishing, provisioning ecosystem services may also need to be considered. Because of these overlaps and the intangible nature of cultural ecosystem services, they are generally difficult to study, and as a result, are typically not as commonly considered compared to other more readily definable ecosystem services (Chan et al. 2012; Milcu et al. 2013; Díaz et al. 2018). However, cultural ecosystem services can be among those that are the most strongly felt by individuals and communities (Millennium Ecosystem Assessment 2005). Below, we explore the five cultural ecosystem service categories related to lake and river ice in more detail.

Ceremonial

Spiritual connections to the environment are embedded in all major religions (de Groot et al. 2005) and ice-covered inland waters have a cultural value in religion (Magnuson and Lathrop 2014). Since the 16th century, Russian Orthodox Christians have celebrated Epiphany by immersing themselves into icy rivers and lakes (Bushkovitch 1990). Another example occurs in the U.S.A. When ice conditions permit, as many as 2000 people trek out on ice-covered Lake Michigan each year to view a large statue of a crucified Christ at the bottom of the lake near Petoskey, Michigan (as described in popular press articles). Many regard this as a spiritual or religious experience. There are also spiritual ceremonies on some Inner

Mongolian and Chinese lakes as part of festivals celebrating the traditional use of under-ice nets for ice fishing that date back thousands of years. The ceremonies historically mark the start of the ice fishing season (as described in popular press articles). Two well-documented examples, a statue procession on Lake Constance and an ice ridge spiritual tradition on Lake Suwa, are described in the Empirical Evidence section.

Artistic

Inspiration and aesthetic appreciation focused on ice-covered lakes and rivers are seen in classic and modern works of art and writing with a variety of themes such as landscapes, activities on the ice (e.g., skating, spiritual ceremonies), physical processes (e.g., ice breakup, ice ridges), and ice patterns. For example, renowned 17th-century landscape painters of the Dutch Golden Age, e.g., Jacob von Ruisdal, painted frozen rivers and canals in the winter. Ansel Adams captured ice-covered Precipice Lake in the Sierra Nevada range of Sequoia National Park in his work titled *Frozen Lake and Cliffs* in 1932. Many famous works by unnamed artists also exist such as a celebrated painting titled the *Ice Skating Game*, depicting skating in China during the 18th-century Qing Dynasty (as described in Liu et al. 2017). In recent years, we have been exposed to artistic expressions of nature through different social media platforms, often without even being aware of them. For example, Instagram, a social media platform for capturing moments using pictures, highlights the aesthetics and inspiration of ice-covered lakes through quantifying the number of public posts using identified hashtags (#FrozenLake: 411,000 public posts, #IceArt: 56,000 public posts as of July 2019).

Education and research

Education and research related to lake and river ice can be formal and informal and includes natural history, citizen science, and traditional knowledge (de Groot et al. 2005). Records kept by casual observers on ice freeze and thaw dates illustrate one example. These records were not collected for scientific reasons, some predate weather records extending back as far as the 15th century, and they represent some of the longest known ice phenology records (Magnuson et al. 2000; Sharma et al. 2016). Instead, many records were collected because the observers were interested in monitoring the natural history of their surroundings, likely providing them with knowledge benefits. In modern times, citizen scientists and natural history enthusiasts contribute to ice phenology records in more formalized networks (e.g., citizen observer for Minnesota U.S.A. Department of Natural Resources, Lake Observer mobile phone app developed by members of the Global Lake Ecological Observatory Network). Another effort, RinkWatch, allows citizen scientists to submit information about ice skating conditions for outdoor ponds and rinks across North America, resulting in at least one publication to date showing reduced skating with recent warming (Damyanov et al. 2012).

Outdoor recreation

The types of outdoor recreation on ice-covered lakes and rivers are numerous and provide benefits of physical exercise, social connections, aesthetic enjoyment of nature, identity, and a sense of place (Millennium Ecosystem Assessment 2005). They can also be a source of tourism revenue during a time of year with less frequent visitors (Hunt and Kolman 2012). Recreational sports on the ice include ice skating, ice hockey, ice wind boarding and ice boating, cross-country skiing, and marathons (e.g., Lake Baikal, Russia). Organized recreational events on ice-covered water bodies in northern communities are also common. Many communities across the world hold ice fishing tournaments or winter festivals and carnivals, with many continuing for decades or longer (Dewar et al. 2001). In regions with long-lasting dark and cold winters, outdoor activities provide a motivation for people to get outside and connect with their community (Johnson and Ali 2017). Moreover, some ice-based activities, like casual skating or fishing, require minimal investment by the users, potentially lessening restrictions of participation along class, racial, and gender lines (Johnson and Ali 2017). Of the numerous types of outdoor recreation on ice-covered lakes, we provide examples of the impact of warming winters on ice skating and ice fishing in the Empirical Evidence section.

Subsistence

Subsistence activities using lake and river ice represent a way of life for many indigenous communities. Activities may involve ice fishing, using ice-covered lakes and rivers for hunting routes such as for caribou in Arctic regions, and traversing ice-covered water bodies for access to trapping sites. Subsistence activities are important for individual and community livelihoods because they provide cultural heritage benefits of northern communities as well as fulfill important economic, nutritional, and sociocultural benefits (Arctic climate impact assessment [ACIA] 2005). Ethnographic interviews with indigenous communities in Alaska revealed perceived changes to subsistence activities due to less favorable ice conditions on lakes and rivers with some noting the potential loss for younger generations to learn this traditional way of living from their elders (Herman-Mercer et al. 2011; Moerlein and Carothers 2012; Carothers et al. 2014).

Warm winters and losses in ice-derived cultural ecosystem service and benefits: Empirical evidence

Ceremonial activities

Ceremonial activities represent an important cultural ecosystem service. The benefits provided are numerous, but are generally understudied and underreported (Milcu et al. 2013). Here, we provide two examples about the loss of spiritual traditions associated with declines in lake ice extending back centuries to A.D. 875 in Lake Constance, Germany/Switzerland/Austria (Fig. 2E) and A.D. 1143 in Lake Suwa, Japan (Fig. 2C). In Japan,

scientists have been able to capitalize on the traditional knowledge of Shinto priests to understand how climate has changed since before the Industrial Revolution, using extremely rare direct human observations (Arakawa 1954; Sharma et al. 2016). The data for these examples are deposited in the Data Repository for the University of Minnesota (Knoll et al. 2019).

Catholic procession on the ice

Historians have documented the occurrence of complete ice cover (termed “Seegfrörne”) on Upper Lake Constance back to the 9th century (Rostron 1888; Meichle 1963). However, for earlier recordings, that is, before 1300, no contemporary records exist and the actual extent of ice cover is unclear (Meichle 1963; Dobras 1992). During the ice cover event of 1573, a statue of John the Apostle was carried across the lake from Münsterlingen (Switzerland) to Hagnau (Germany) (linear distance: 7.5 km). The reason for this first transport is unclear and may be related to the reformation and iconoclasm taking place in Münsterlingen before this time. However,

based on this event, a religious procession was initiated during which the statue was transferred from one shore of the lake to the other during events of complete ice cover when the ice was thick enough to carry this procession. In Lake Constance, the number of extreme cold years peaked between 1375 and 1574 (Fig. 3A). Since 1674, Lake Constance has frozen only six times, most recently in 1963. During this last event in 1963, the statue was accompanied across the lake from Hagnau to Münsterlingen (Fig. 2E). Thus, the statue remains in the church of Sankt-Remigius in Münsterlingen until the lake freezes again.

Shinto ceremony on the ice

In 1443, a Shinto priest began a tradition of recording the appearance of a sinusoidal ice ridge, known as an *omiwatari* in Japanese, on Lake Suwa. Since then, many generations of priests have continued to update this archive. For the Shinto and local community, the appearance of the *omiwatari* is a message from God. The Shinto legend states that the *omiwatari*



Fig. 2. Examples of human uses of ice-covered lakes and rivers discussed in this paper are indicated by symbols on the map displaying the geographical distribution of regions experiencing a seasonally ice-covered period (gray gradient) as modeled by Weyhenmeyer et al. 2011. Photo credit: (A) Yukari Hori, Feb 2015 (insert: reprint from CBC News, Dec 2011). (B) Matilda L. Andersson, Mar 2018 (insert: Robert M. Griffin, Feb 2012). (C) Reprint of photo from Yatsurugi Jinja Shrine, courtesy of J. J. Magnuson. (D) Lesley Knoll, Feb 2018. (E) Heinz Finke, reprint from Dobras (1992), Winter 1962/1963.

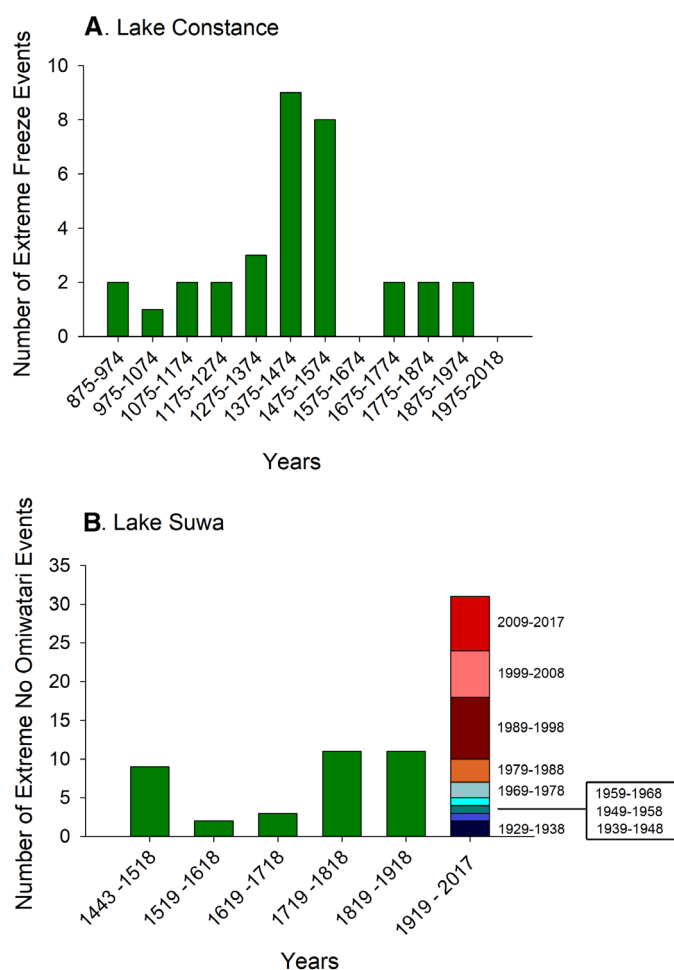


Fig. 3. (A) The number of extreme cold years in Lake Constance, Germany, from 875 to 2018 defined as years in which a complete freezing of upper Lake Constance is documented. (B) The number of extreme warm years (defined as the absence of *omiwatari*) in Lake Suwa, Japan, from 1443 to 2017. More recent years (1919–2017) are divided by 10-year increments. Note that 1919–1928 had zero extreme warm years.

is formed by the footsteps of the male God Takeminakata when he would cross the lake to visit the female god Yasakatome at her shrine on the other side of the lake. Upon confirmation of the *omiwatari* by the Yatsurugi Shrine in Suwa, a purification period of 3 d to 1 week begins. During the purification period, the monks hang a sacred straw rope over the entrance to their house and purify their minds, bodies, and houses. The Shinto priests conduct the formal *omiwatari* ceremony on the lake ice and have used the size, position, and direction of the *omiwatari* in efforts to predict the rice harvest for centuries (Arakawa 1954; Magnuson et al. 2000; Hanazato 2001; Sharma et al. 2016; Miyasaka, pers. comm.).

We obtained data on the occurrence of the *omiwatari* from the Shinto shrine from Tadashi Arai based on Arakawa (1954) and subsequently to 2018 from conversations with the

current Shinto priest of the Yatsurugi Shrine, Miyasaka. The number of extreme warm events, defined as the absence of *omiwatari*, in Lake Suwa, Japan, has increased over the past six centuries culminating with 31 no *omiwatari* events in the last 100 years (Fig. 3B). Twenty-one of these extreme warm events have occurred since 1989 (Fig. 3B) as compared to the first 250 years of the Lake Suwa *omiwatari* record when the lake did not freeze three times (Fig. 3B). The absence of the *omiwatari* was once associated with widespread famine in the Suwa region (Mikami 2008) and now represents a rapidly warming climate (Sharma et al. 2016).

These two examples, Lake Constance and Lake Suwa, illustrate how changing ice conditions may influence ceremonial activities and the associated cultural benefits. This represents challenges for northern communities given documented ice cover declines worldwide (Magnuson et al. 2000; Benson et al. 2012; Sharma et al. 2016) and future projections (Sharma et al. 2019). Spiritual connections to the natural world are embedded in major religions (de Groot et al. 2005) and some of these connections are with seasonally ice-covered water bodies.

Outdoor ice skating

Outdoor ice skating may have first been used as a form of transportation thousands of years ago with the aid of bone skates (Formenti and Minetti 2008). In modern times, ice skating provides important recreational benefits such as activity, social capital, and cohesion, as well as a sense of place and connection to one's heritage (Visser and Petersen 2009; Liu et al. 2017). In many areas, including Canada, the practice of ice skating is strongly coupled with identity (Johnson and Ali 2017).

Winter sports such as outdoor ice skating are a longstanding tradition and a popular part of the culture in Nordic countries. One example highlighting this is a 200 km Dutch ice skating race leading past 11 historical cities of the Friesland province in Northern Netherlands, which dates as far back as 1749 (Visser and Petersen 2009). Since the first official Eleven Cities Tour in 1909, only 15 official tours have been organized with the most recent in 1997. Due to the popularity and infrequency of the Eleven Cities Tour, a skating race in Sweden was created with the hope of providing a more reliable venue in the Nordic region. The Vikingarännet (translated from Swedish as “The Viking ride”) began in 1999 as an 80-km ice skating race on seasonally ice-covered Lake Mälaren running along an old Viking route from Uppsala to Stockholm in Sweden (Fig. 2B).

The Vikingarännet ran from 1999 to 2017, but was indefinitely canceled in 2018 until a more financially sound model could be found as unpredictable ice-cover conditions with likely cancellation of the race caused financial strain on the organization. This unpredictability mirrors long-term records for many Swedish lakes that show earlier ice breakup over time (Weyhenmeyer et al. 2004). Since we lack long-term records beyond general ice cover trends, we explored how

warmer vs. cooler winters affected the Vikingarännet race. Using the ice skating race information provided on the official Vikingarännet website (<http://vikingarannet.com>), we compiled data on the annual ice skating route from 1999 to 2017 into three categories: (1) track denotes the direct ice skating route that started near Uppsala and ended near Stockholm, (2) loop refers to an altered ice skating route with multiple laps and the same start and end location, and (3) none represents years where the ice skating race was canceled. Track occurred when the lake was completely frozen, while loop occurred when areas of the lake were not frozen or were unsafe for skating. We then compared average winter air temperature data from Uppsala (obtained from SMHI; <https://www.smhi.se>) for the months December through February to categorical ice skating route data (ANOVA test). These months were chosen as they represent the duration which ice-cover conditions were monitored leading up the race in mid-February. A Tukey's post hoc test was then performed to determine differences between ice skating route categories. The data used are deposited in the Data Repository for the University of Minnesota (Knoll et al. 2019).

Winter air temperatures influenced the ice skating route (ANOVA, $F = 10.77$, $p < 0.01$, Fig. 4). Winters were colder in years when the ice skating route was not changed (air temperature averaged -3.6°C). Comparatively, in years when the ice skating route was changed or canceled, the mean winter air temperature (-0.89°C and -0.18°C , respectively) was significantly higher (Tukey's HSD $p < 0.01$), with no significant difference between them (Tukey's HSD $p = 0.67$).

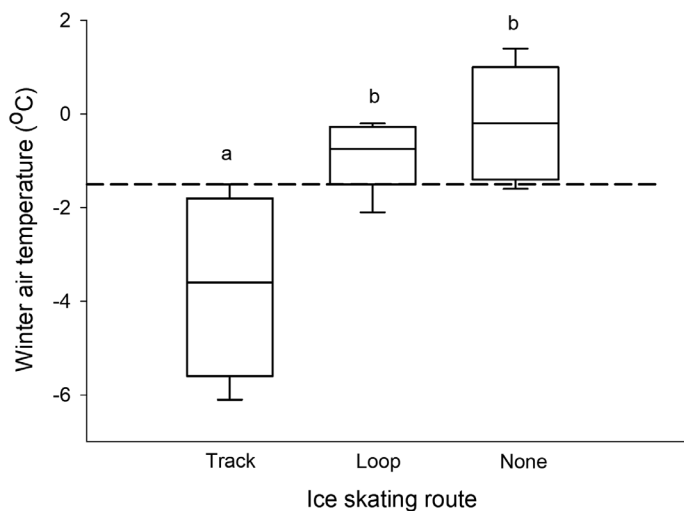


Fig. 4. The relationship between the ice skating route of the Vikingarännet race (1999–2017) and winter air temperature (Dec–Feb). The track route, with winter air temperature consistently below -1.5°C (dashed line), had significantly lower average winter air temperature compared to the loop and none route (Tukey's HSD $p < 0.01$), as indicated by lower case letters in the figure. Boxes indicate the 25th percentile, median, and 75th percentile.

Our results showed that the Vikingarännet ice skating race routes were either altered or completely canceled in warmer winters. This confirms that warmer winters pose a serious threat to the benefits supported by ice skating. Sporting events on ice-covered inland waters serve as part of the cultural identity as a source of inspiration and knowledge (e.g., Ramshaw and Hinch 2006). Uncertainties in ice-covered conditions at these types of events, including last minute cancellations, cause economic strain for organizers, and a loss of motivation to train and willingness to participate the following year for participants. In certain cases, artificial ice can be used as a substitute and some communities facing a loss in stable ice skating conditions on natural water bodies have adapted by creating indoor and simulated outdoor ice skating rinks (Liu et al. 2017). Other events are being relocated to regions with more stable ice and snow conditions (e.g., Scott et al. 2018). In addition to being costly, replacing natural frozen water bodies with artificial ice rinks or relocating events may restrict participation along class, racial and gender lines, changing outdoor ice sports from an unstructured and inclusive activity to an expensive, confined, and exclusive activity (Johnson and Ali 2017).

Ice fishing

Ice fishing is common in regions with ice-covered inland waters and may be categorized as both recreation and subsistence. Ice fishing provides recreational opportunities even in very cold regions where ice fishing shelters are often used to provide heat and other amenities. In some areas, ice anglers form an informal community of ice shanties on lakes resulting in social benefits for these anglers (Van Assche et al. 2013) that, in addition to recreation, provide a sense of place, social capital and cohesion, and cultural identity.

Ice fishing has a long and continuous history in Minnesota. This is reflected in the number of licenses sold for ice house permits, which has increased steadily from around 40,000 in the 1950s to about 110,000 in the 1990s (Pierce and Cook 2000). For some lakes, winter represents a more active fishing period than the summer (Van Assche et al. 2013). At the same time, lakes in the state with long-term records mirror worldwide trends of declining ice cover (Johnson and Stefan 2006; Jensen et al. 2007).

We examined how warmer vs. cooler winters affected ice fishing in Minnesota (Fig. 2D) by examining ice fishing tournaments. We used data from ice fishing tournament permits (winters 2005/2006–2016/2017) from the Minnesota Department of Natural Resources and air temperature data from NOAA's National Climate Data Center. The northern portion of Minnesota is often cooler than the central and southern areas of the state. Therefore, we used this natural gradient to assess if warmer winters influenced fishing tournaments differently in these regions. We calculated average November through January air temperature by NOAA state climate divisions since these months reflect both ice-on and ice formation

through early February for Minnesota. We only examined trends in the central and northern regions because the southern region had few tournaments (~10 per year). We found that during the study years, winter air temperature was significantly colder in the northern region than the central region (Wilcoxon signed-rank test, $p < 0.001$). The data used are deposited in the Data Repository for the University of Minnesota (Knoll et al. 2019).

In general, the northern region in Minnesota had fewer fishing tournament permits issued and fewer tournament participants per year than the central region (Fig. 5A,B). The northern region also had fewer cancellations with many years of no canceled events (percent of cancellations range 0–14%, Fig. 5C). The average winter air temperature did not explain the percentage of canceled tournaments in the northern region (Kendall rank correlation, $\tau = 0$, $p > 0.05$, Fig. 5C) and the northern region never experienced average winter air temperature warmer than -5.3°C during the study period. The central region had a large range in cancellations each year from a low of zero to a high of 15 tournaments (percent of cancellations range 0–34%, Fig. 5D). In the central region, winter air temperature was related positively to the percentage of canceled tournaments (Kendall rank correlation, $\tau = 0.52$, $p < 0.03$,

Fig. 5D). Higher cancellations in the central region occurred when average winter air temperatures were -4°C or warmer.

Reduced ice fishing during warmer winters, as highlighted in the fishing tournament results, has the potential to influence parts of the social network, economy, food security, and overall wellbeing of northern communities. Many recreational anglers noted that in the winter, they fish more for the social aspect whereas the focus is on catching fish during the summer (Van Assche et al. 2013). On the other hand, some lakes can experience more fishing effort from ice fishing than summer fishing, which can account for a large portion of annual fish harvesting such as in Lake Peipsi, Estonia (Orru et al. 2014). Ice fishing also can be an important part of local revenue during the winter season. In Minnesota, the annual Brainerd Jaycees Ice Fishing Extravaganza has been estimated to contribute 1 million USD and the International Eelpout Festival has been estimated to contribute \$800,000 USD to their local economies (as described in popular press articles). Both of these tournaments have experienced delays or event modifications in recent years as a result of thin ice. Although long-term analyses of the influence of climate change on ice fishing activity has not been conducted, climate projections suggest that ice fishing may be negatively affected by warmer

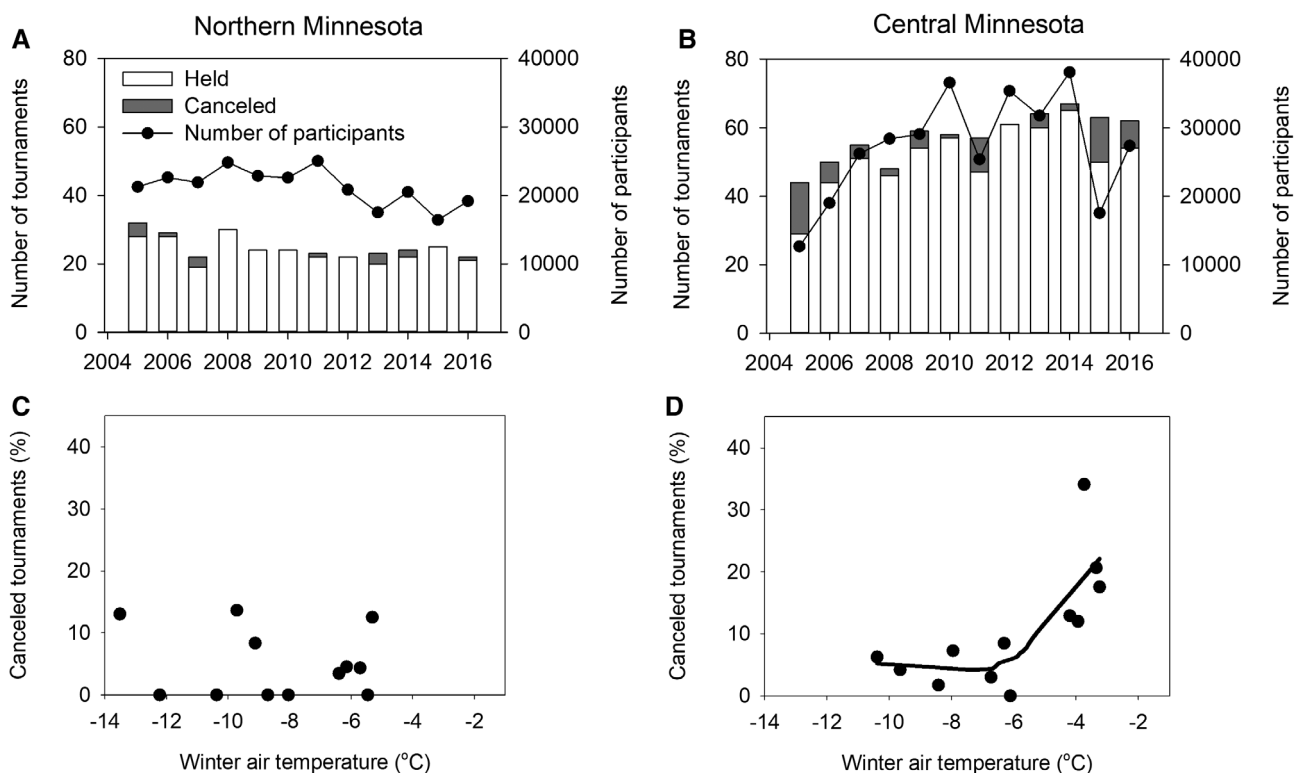


Fig. 5. (A, B) The annual number of held and canceled ice fishing tournaments in northern and central Minnesota and the number of participants. Relationship between the average winter air temperature (Nov–Jan) and the average percentage of canceled tournaments in (C) northern Minnesota (Kendall rank correlation, not significant) and (D) central Minnesota (Kendall rank correlation, $\tau = 0.52$, $p < 0.03$, smoothed LOESS line).

winters in the future (Dawson and Scott 2010; Hunt and Kolman 2012).

Winter ice roads

Ice roads occur throughout northern areas in the winter. For example, the Apostle Islands in Lake Superior are connected to Bayfield, Wisconsin, via an ice road that is also used to transport children to school using a motorized ice sled during thinner ice conditions and a larger vehicle on the thicker ice road (Magnuson and Lathrop 2014). Here, we explore ice roads in Canada as a proxy for the numerous benefits they provide to isolated indigenous communities (e.g., social capital and cohesion, place and heritage, knowledge, and identity).

Winter ice roads in northern Canada consist of ice roads over land, frozen lakes, rivers, and creeks (ACIA 2005). These roads often are used in the northern parts of Northwest Territories, Manitoba, and Ontario (Andrey et al. 2014). In particular, the winter road networks in northern Manitoba and Ontario serve 18 and 31 remote indigenous communities, respectively (Government of Ontario 2017; Province of Manitoba 2017), and represent the most extensive networks in northern Canada. Surface air temperature, precipitation, snowfall, and wind play a significant role in determining the viable operating season of winter ice roads (ACIA 2005; Knowland et al. 2010; Hori et al. 2017). In recent years, the average opening date of winter roads has been delayed and the quality of the roads have been reduced as a result of warming winters (ACIA 2005; Chiotti and Lavender 2008; Furgal and Prowse 2008; Blair and Sauchyn 2010; Hori et al. 2018a). We examined the opening dates of the James Bay Winter Road in northern Ontario (Fig. 2A) in recent years and compared these with freezing degree-days. The James Bay Winter Road runs parallel to James Bay, and by necessity, must cross frozen rivers and swamps to connect communities in the south with those in the north. We identified the relationship of freezing degree-day accumulations to the opening dates of the James Bay Winter Road from 2005 to 2018 (sensu Hori et al. 2017). The latest road opening dates were obtained from the Kimeskanemenow corporation website (<http://www.winterroadcompany.ca/>). The daily mean temperature at the Moosonee weather station (51°16'N, 80°39'W) was obtained from Environment Canada (http://climate.weather.gc.ca/index_e.html). Freezing degree-days were calculated as a sum of the daily mean temperatures below the freezing point (0°C) of freshwater for a given time period with units in degree-days (Hori et al. 2017). We examined the freezing degree-day accumulations from 01 October to 31 December as a preconditioning period of winter road season. The data used are deposited in the Data Repository for the University of Minnesota (Knoll et al. 2019).

The mean opening date for the James Bay Winter Road between 2004/2005 and 2017/2018 was 18 January (with two missing years, 2006/2007 and 2007/2008). When we extended the time-series of Hori et al. (2017) for the Hudson-James Bay

region, the relationship between winter road opening and freezing degree-days was significant; the winter road opened later in warmer winters (Kendall rank correlation, $\tau = -0.503$, $p < 0.05$, Fig. 6A), and conversely, cooler winters permitted an earlier opening of the winter road. There was no significant trend toward a later opening of the winter road over time, but we note the limited time span of our time series (Mann-Kendall trend test: $p = 0.2$, $n = 14$; Theil-Sen slope: $+0.72$ d, Fig. 6B).

Our results have many implications since winter roads facilitate important social, cultural, and economic benefits in remote northern communities (Chiotti and Lavender 2008; Furgal and Prowse 2008). A recent study examined the current vulnerability of the Fort Albany First Nation in northern Ontario to physical, social, and economic impacts associated with changing viability and longevity of winter roads, as well as river ice regimes (Hori et al. 2018b). In this study, 93% of winter road users in the community reported that the James

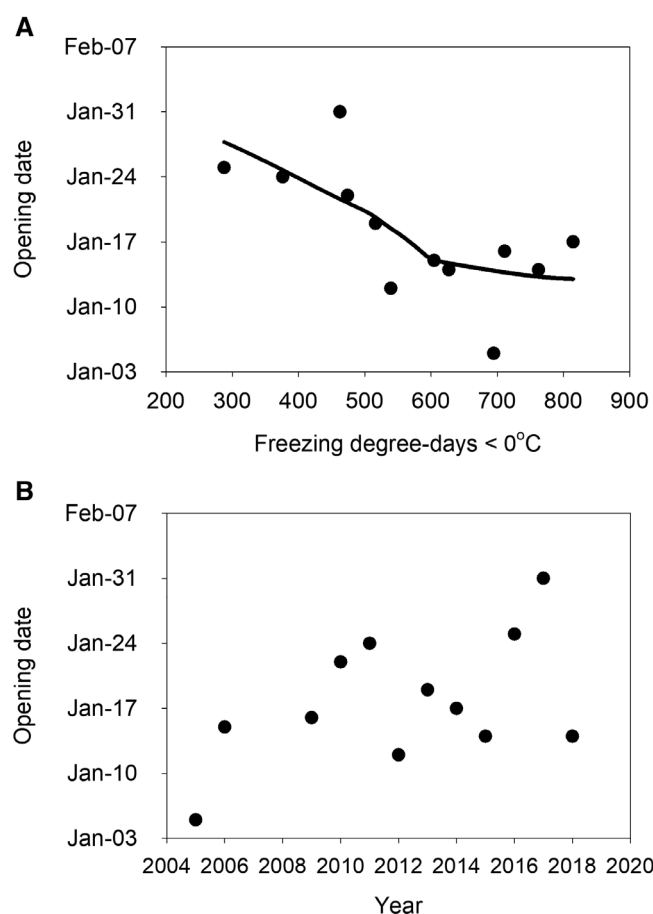


Fig. 6. (A) Relationship between freezing degree-days from Oct to Dec and the James Bay Winter Road opening dates from 2004/2005 to 2017/2018 (Kendall rank correlation, $\tau = -0.503$, $p < 0.05$, smoothed LOESS line) and (B) time series of the opening dates of the James Bay Winter Road from 2004/2005 to 2017/2018 (Mann-Kendall trend test, not significant).

Bay Winter Road is important to the community for social (i.e., visit family and friends), mental health (i.e., feel less isolated), and financial (i.e., cheaper to travel) reasons. In addition, winter ice road construction and maintenance can be expensive. In 2003–2004, the Government of Ontario spent \$3 million CAD to construct and maintain approximately 3000 km of winter roads in northern Ontario; in 2017–2018, they invested \$5.8 million CAD (Government of Ontario 2004, 2017). Winter road construction is much more affordable than permanent roads (e.g., ~ \$1300/km vs. \$0.5–1 M/km CAD), permitting social and commercial activity in remote areas that would otherwise not be economical (National Research Council 2013).

Future research directions

The cultural ecosystem services related to seasonally ice-covered lakes and rivers are diverse (Fig. 1) as are the potential future research directions. Here, we highlight three areas for future research which are described in more detail below: (1) considering cultural ecosystem services derived from lake and river ice in the context of coupled natural and human systems, (2) using unexploited datasets to quantify recreational disruptions at local to global scales, and (3) assessing the economic impacts of losing inland ice on cultural ecosystem services. We focus on areas that might be considered more directly quantifiable because they highlight changes that are observable and may represent indicators that are meaningful for a diverse audience including decision makers. This approach also takes advantage of our strengths, which are largely quantitative. However, we recognize that other cultural ecosystem services and benefits (e.g., cultural heritage, sense of place, inspiration) are also being lost and require attention using diverse methods and teams (e.g., ethnographic interviews, cultural consensus analysis, and combining qualitative and quantitative methods).

Coupled natural and human systems

An exciting avenue of future research is understanding the dynamics between inland ice and ecosystem services through the lens of the coupled natural and human systems framework. In coupled natural and human systems, the interaction between humans and nature is considered as well as the complex patterns, feedbacks, and processes of these interactions (Liu et al. 2007). This requires an integrated approach to combine the physical, chemical, and biological components of the natural system with the behavioral, social, and economic components of the human system. For the empirical examples provided in our paper, we quantified how nature (i.e., ice cover) influences humans (various activities on the ice), but did not specifically examine the interactions or feedbacks. Future research should include a coupled natural and human systems approach. For example, scientists acknowledge the complex interactions and feedbacks between humans and

fisheries on open-water lakes; we suggest much is left to learn about this coupling by incorporating ice-covered lakes and ice fishing. A warming climate is altering fish communities, population sizes, and geographical distributions of native and invasive fishes (Hansen et al. 2016; Van Zuiden and Sharma 2016). In turn, this may affect the timing and intensity of fishing pressure in both the winter and summer, ultimately influencing the human uses derived from fishing in these two seasons with implications for fisheries management. These approaches, including incorporating the winter season, are beginning to be considered by scientists (Hunt et al. 2016), but more work is necessary to understand, manage, or conserve the whole system (i.e., natural and human combined) more completely.

Unexploited datasets

The cultural ecosystem services and benefits provided by ice cover to recreational activities and events are often documented in various archives. Our efforts revealed that many additional potential long-term records exist and are housed in nontraditional locations such as recreational clubs or organizations, businesses, newspaper and popular press articles, social media platforms, and with individuals. For example, although we focused on fishing tournament events in the U.S.A. and an ice skating race in Sweden, many other events globally take place on lake and river ice each year (e.g., ice regattas, festivals, and ice hockey tournaments), often dating back decades or longer (Dewar et al. 2001). These events are part of long-term records in many communities. Furthermore, since many ice activities are tied with local economies or tourism, we suggest that local businesses or chambers of commerce (e.g., Boards of Trade/Commerce) may be able to provide additional records. Other unexploited datasets can be found in more traditional locations such as local, regional, and federal agencies (e.g., various permit types for recreational events and activities). Our empirical examples were of either a single lake or relatively small geographic area, but there is a need for further analyses in more locations as well as synthesis efforts at broader regional to global scales.

Economic impacts of losing lake and river ice

The extent to which reductions in ice cover will influence economies that rely on ice is largely unknown. Losses may be felt in many ways from tourism associated with organized winter events to ice road use to fishing for subsistence and recreation. For example, winter festivals such as the Quebec Carnival rely on various ice-themed activities like canoeing on the St. Lawrence River (ice-covered or partially covered). In 1999, revenue from this festival was \$48 million CAD (Dewar et al. 2001). Ice angler activity illustrates another example; approximately 2 million ice anglers spent a total of nearly 38 million days ice fishing across the USA (excluding the Great Lakes) and spent \$178 million USD on ice fishing equipment (U.S. Department of the Interior 2011). Many of these anglers will support businesses near these ice-covered inland

waters, thus there will likely be many consequences of climate change related projections of unsafe or unreliable ice conditions (Sharma et al. 2019). Changing ice conditions are already influencing subsistence food fisheries in northern Canada; for some communities and individuals, subsistence costs are increasing from unreliable ice while at the same time, fresh food in the market is two to three times higher than in southern parts of Canada (Furgal and Prowse 2008). The total economic impact of losing inland ice is currently not known and deserves attention. We suggest a focus on assessing the magnitude across a broad regional or global scale. Furthermore, part of these efforts should consider how communities and individuals are already confronting and adapting to the loss of lake and river ice, and if they can shift to open-water activities.

Conclusions

With climate change, inland ice is being lost around the world (Magnuson et al. 2000; Benson et al. 2012; Sharma et al. 2019). Subsequently, the wide array of cultural ecosystem services provided by lake and river ice is being lost. We provide a framework for understanding ice-based cultural ecosystem services and the benefits that they provide humans. We also highlight empirical evidence on the loss of spiritual ceremonies, ice skating races, ice fishing tournaments, and prolonged use of winter ice roads related with climate variability (i.e., warmer vs. cooler winters) in recent decades. Together, our synthesis and empirical examples represent one of the most comprehensive assessments on the diverse ice-related cultural ecosystem services in geographically disparate regions. We recommend continued studies to better assess how ice loss may erode cultural ecosystem services, the use of integrative approaches to evaluate the interplay between ice-covered inland water bodies and society to recognize the full benefits of this natural resource, and understanding the role of adaptations to changing ice conditions.

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