Received: 16 December 2020 | Revised: 25 March 2021 | Accepted: 1 April 2021

DOI: 10.1002/wat2.1526

OVERVIEW

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Arctic wetland system dynamics under climate warming

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Funding information
Vetenskapsrådet, Grant/Award Number: 2017-00608

Edited by: Lenka Slavikova, Associate Editor, and Stuart N. Lane, Editor-in-Chief

Abstract

Warming and hydrological changes have already affected and shifted environments in the Arctic. Arctic wetlands are complex systems of coupled hydrological, ecological, and permafrost-related processes, vulnerable to such environmental changes. This review uses a systems perspective approach to synthesize and elucidate the various interlinked responses and feedbacks of Arctic wetlands to hydroclimatic changes. Starting from increased air temperatures, subsequent permafrost thaw and concurrent hydrological changes are identified as key factors for both shrinkage and expansion of wetland area. Other diverse factors further interact with warming, hydrological changes, and permafrost thaw in altering the Arctic wetland systems. Surface albedo shifts driven by land cover alterations are powerful in reinforcing Arctic warming, while vegetation-related factors can balance and decelerate permafrost thaw, causing negative feedback loops. With the vast amounts of carbon stored in Arctic wetlands, their changes in turn affect the global carbon cycle. Overall, the systems perspectives outlined and highlighted in this review can be useful in structuring and elucidating the interactions of wetlands with climate, hydrological, and other environmental changes in the Arctic, including the essential permafrost-carbon feedback.

This article is categorized under:

Water and Life > Nature of Freshwater Ecosystems
Water and Life > Stresses and Pressures on Ecosystems
Science of Water > Water and Environmental Change

KEYWORDS

Arctic wetlands, carbon dynamics, climate feedbacks, environmental systems, permafrost

1 | INTRODUCTION

The Arctic is experiencing warming at more than twice the global average in response to increasing greenhouse gas (GHG) concentrations and climate change due to anthropogenic forcing (Serreze & Francis, 2006). This has drastic impacts on Arctic environments, including an intensification of the hydrological cycle (Rawlins et al., 2010), melting of glaciers and ice sheets (Olsen et al., 2011), thawing of permafrost (Biskaborn et al., 2019), ecological regime shifts

(Karlsson, Bring, Peterson, Gordon, & Destouni, 2011), and enhanced ecosystem disturbances (McGuire et al., 2009), which results in land cover changes (Quinton, Hayashi, & Chasmer, 2011).

Wetlands in the Arctic represent landscapes of particular interest as they link hydrological, ecological, and permafrost processes (Woo, 2012; Woo & Young, 2006). Permafrost underlays large parts of the Arctic (Gruber, 2012) and is defined as ground conditions that remain at or below 0°C for at least two consecutive years (French, 2018). Depending on the ground thermal regime, permafrost is susceptible to temperature changes resulting in active layer deepening and permafrost degradation (Biskaborn et al., 2019; Romanovsky et al., 2017). In addition to large-scale temperature trends, surface and ground temperatures and permafrost thaw are also influenced by various local factors, such as vegetation (Karlsson et al., 2011), topography and snow cover (Vercauteren, Lyon, & Destouni, 2014), and soil properties (Selroos, Cheng, Vidstrand, & Destouni, 2019), which complicate projection of future permafrost evolution (Shur & Jorgenson, 2007). As such, Arctic wetlands are vulnerable to climate and other environmental changes that can lead to expansion or shrinkage of wetland area (Avis, Weaver, & Meissner, 2011; Walvoord & Kurylyk, 2016; Woo, 2012).

Climate-driven shifts in Arctic wetland landscapes thus entail intricate processes, as various environmental factors interact with each other leading to domino effects and feedbacks (Eugster et al., 2000; Schuur et al., 2015; Shur & Jorgenson, 2007; Sim et al., 2019). Wetlands also fulfill important ecosystem services in the Arctic, including storing about 50% of the world's soil carbon (Coffer & Hestir, 2019; Tarnocai et al., 2009), and therefore changes in them and in the area they cover are of high ecological relevance (Maltby & Acreman, 2011; Woo & Young, 2006). In direct relation to Arctic wetlands, permafrost also acts as a crucial factor influencing wetland coverage (Smith, Sheng, MacDonald, & Hinzman, 2005) and carbon dynamics (Schuur et al., 2015).

It is therefore essential to investigate the structures and dynamics of Arctic environmental changes related to wetlands, including instabilities and imbalances that may become irreversible once certain tipping points are passed (Lenton et al., 2019). For example, Hinzman et al. (2013) investigated the Arctic as an integrated system and emphasized the importance of systems thinking when assessing the impacts of climate change on Arctic environments. Analyzing the system structures in Arctic environments is also vital for understanding such impacts on local communities and improves models and projections of future changes (Hinzman et al., 2013).

This review follows a systems perspective approach to synthesize and elucidate the various interlinked responses and feedbacks of Arctic wetlands to climate change, including a range of relevant influencing factors and their interactions. The review is based on both case studies and review articles examining Arctic wetlands and impacts of climate change on related environmental systems. As permafrost is an important influence, dynamics in the High- and Sub-Arctic are considered in the review. To follow and illustrate the systems perspective, conceptual casual loop diagrams are used to depict key interactions between relevant system parameters, including positive and negative link polarities and evolving feedback mechanisms. Characteristics of Arctic wetlands and impacts of warming and permafrost thaw are presented that, under different environmental circumstances, can lead to either shrinkage or expansion of wetland area, or both in different parts of the regional landscape. Furthermore, feedback mechanisms that reinforce or balance warming and permafrost degradation in the Arctic are examined, including surface albedo feedbacks and hydrological and ecological interactions with the ground thermal regime. As wetlands represent important environments for carbon storage and cycling, processes and feedbacks related to carbon dynamics in Arctic wetland systems are also discussed.

2 | CHARACTERISTICS AND IMPORTANCE OF ARCTIC WETLANDS

Wetlands lie at the transitional interface between terrestrial and aquatic systems and vary in size, location, duration of flooding, species hosted and degree of management, which complicates a comprehensive definition (Mitsch & Gosselink, 2015). However, three common attributes are ubiquitous to all wetlands: (1) the presence of water, that is, surface water and/or saturated soil conditions; (2) particular soil characteristics including slow decomposition and organic matter accumulation; and (3) plant communities adapted to wet conditions (hydrophytes) (Mitsch & Gosselink, 2015).

In the Arctic, wetlands cover ~7% of the nonglaciated area (Walker et al., 2005) and around 53% of the global wetland area is located north of 50°N (Aselmann & Crutzen, 1989). Three major factors favor Arctic wetland occurrence (Winter & Woo, 1990; Woo & Young, 2012): (1) Climate (precipitation and evaporation) affects wetland occurrence with generally dry Arctic conditions but also low evaporation due to the low energy supply (Serreze & Barry, 2014) and, therefore, wetlands do form when water supply by precipitation or adjacent surface flow is ensured; (2) Topography with depressions and lowlands where water can accumulate and with slope gradients directing water flows to these; (3) Soil type with relatively low permeabilities of formerly glaciated soils (Smith, Sheng, & MacDonald, 2007), and peat soils with high water-holding capacity (Woo & Young, 2012). Wetlands in turn also support peat accumulation as they limit organic decomposition (Ovenden, 1990).

There are different classification schemes for Arctic wetlands. For example, the Canadian classification recognizes four categories based on the wetland hydrology: bogs, fens, marshes and swamps, and shallow water bodies (National Wetlands Working Group, 1997). Bogs and fens are defined based on their water sources; bogs are solely precipitation-fed (ombrogenous), whereas fens are influenced by groundwater (geogenous) (Woo, 2012). Water sources also cause differences in vegetation since ombrogenous wetlands are nutrient poor and develop a cover of *Sphagnum* mosses, while geogenous fens are nutrient rich and dominated by grass and sedge species (van Huissteden, 2020). Marshes and swamps have lakes, rivers, or the sea as their water source (Woo, 2012). Marshes do not support tree growth, whereas swamps may host trees (National Wetlands Working Group, 1997; Zoltai & Vitt, 1995). Shallow water bodies describe a transitional state between wetland and open water, that is, lakes (National Wetlands Working Group, 1997) and are characterized by ponding and seasonal fluctuation in water levels (Zoltai & Vitt, 1995).

Woo and Young (2006) divide High-Arctic wetlands into patchy and extensive wetlands. Patchy wetlands are <10 km^2 in area and have several water sources, for example, snowmelt, groundwater, lateral inundation, lakes, and permafrost. Extensive wetlands occupy low-gradient areas and plains including deltas, river, and coastal plains (Woo & Young, 2006). According to the Ramsar Convention and its classification scheme, Arctic wetlands include shallow lakes, rivers and deltas, coastal marshes, shallow sea waters, non-forested and forested peatlands which in turn entail permafrost featured wetlands, such as polygonal mires, kettle-hole mires in thermokarst depressions, valley fans, and shallow peat tundra (Minayeva & Sirin, 2009). There is no uniform and transnational classification system for wetlands in the Arctic, instead countries use different definitions and classifications in their national inventories (Finlayson & van der Valk, 1995). This review focuses on Arctic wetlands as an essential part of the environmental system as a whole, whereas differentiating between various different wetland types is outside the scope of this contribution.

In the High Arctic, wetlands are underlain by continuous ice-rich permafrost which is facilitated by the ample ground moisture (Roulet & Woo, 1986; Woo, 2012). Permafrost acts as an aquitard, due to its low hydraulic conductivity, which promotes formation and persistence of wetlands (Walvoord & Kurylyk, 2016). Ice wedges create the typical polygonal features in the tundra where water accumulates either in cracks formed by the ice wedges or in depressions between wedges (Liljedahl et al., 2016). Not only in Sub-Arctic areas with less permafrost, but also in High-Arctic periglacial areas with deep permafrost (Johansson et al., 2015), wetlands can impede survival of ground ice due to the high heat capacity of water leading to formation of taliks, including total through-taliks by complete thawing of permafrost (Kurylyk, Hayashi, Quinton, McKenzie, & Voss, 2016). In such landscapes, permafrost can be adjacent to a wetland or beneath insulating peat plateaus forming palsa mires (Seppälä, 1982).

Arctic wetlands are also ecosystems of great importance for Arctic communities. At high latitudes, where precipitation is generally limited, wetlands may be significant freshwater sources, and recharge, filter, and buffer water for downgradient environmental systems (Mitsch & Gosselink, 2015; Quinton et al., 2011), with which they can be hydrologically connected also over large distances (Bosson, Sabel, Gustafsson, Sassner, & Destouni, 2012) through both surface and subsurface flow pathways (Bosson, Selroos, Stigsson, Gustafsson, & Destouni, 2013). Due to their rich vegetation, wetlands are also valuable grazing grounds and habitats in polar desert landscapes (Seifollahi-Aghmiuni, Kalantari, Land, & Destouni, 2019) and represent vital ecosystems for fish, waterfowl and other birds (Greb, DiMichele, & Gastaldo, 2006; Jefferies, Rockwell, & Abraham, 2011), while also providing important carbon sequestration and storage (Coffer & Hestir, 2019; Tarnocai et al., 2009). After deglaciation, low temperatures and waterlogged conditions converted Arctic wetlands into carbon sinks (Smith et al., 2004). However, warming and associated permafrost thaw could turn these wetlands into sources of carbon that increase GHG emissions to the atmosphere (Coffer & Hestir, 2019; Kayranli, Scholz, Mustafa, & Hedmark, 2010; Schuur et al., 2015). In particular, waterlogging can lead to anaerobic decomposition and increased emissions of methane, a more potent GHG than carbon dioxide (Petrescu et al., 2010). Arctic wetlands have also received recent attention for the formation of the potent neurotoxin methylmercury, which readily bioaccumulates in the food chain and thus poses a threat to Arctic wildlife and human populations (AMAP Assessment, 2021). In this context, permafrost acts to control rates of mercury release to wetlands and subsequent methylation (MacMillan, Girard, Chételat, Laurion, & Amyot, 2015).

3 | THE FUTURE OF ARCTIC WETLANDS

Due to the complexity and high variability of Arctic environments, the response of wetlands to warming and concurrent hydrological changes depends on diverse factors. Generally, wetlands can either shrink or expand, or both over larger areas throughout the Arctic (Avis et al., 2011; Karlsson et al., 2011; Kokelj & Jorgenson, 2013; Smith et al., 2005). These shifts may be driven by hydroclimatic and other environmental processes interacting with permafrost thaw (Figure 1). Air temperature and hydrological changes alter water balances in the Arctic wetlands, including by precipitation, snowmelt, groundwater, surface water, and evapotranspiration input and output fluxes (Bring et al., 2016; Carroll & Loboda, 2017; Ge, McKenzie, Voss, & Wu, 2011; Lamontagne-Hallé, McKenzie, Kurylyk, & Zipper, 2018).

Warming and precipitation changes in the Arctic are reported to have led to an intensification of the terrestrial hydrological cycle, with increased rates of evapotranspiration and/or runoff in addition and in response to precipitation increases (Holland, Finnis, Barrett, & Serreze, 2007; Mauritzen, 2012). Projections suggest an increase of more than 50% in Arctic precipitation by the end of the century (Bintanja & Selten, 2014; Kattsov et al., 2007). Moreover, a shift of precipitation from snow to rain is projected and expected to reduce annual snow cover, influencing both the amount of water stored as snow and the timing of meltwater release (Bintanja & Andry, 2017). Decreases in sea ice also increase the amount of sea water available for evaporation, promoting cloud formation, and precipitation (Kopec, Feng, Michel, & Posmentier, 2016). Simultaneously, enhanced evapotranspiration implies loss of terrestrial water (Liljedahl et al., 2011) such that remaining water for runoff through the landscape does not necessarily increase even if precipitation increases (Karlsson, Jaramillo, & Destouni, 2015).

Overall, changes in the Arctic water cycle affect wetland hydrology as indicated in Figure 1. If water influxes increase, this can lead to inundation and expansion of wetlands (Woo, 2012; Woo & Young, 2006), while decreased water influxes accompanied by higher evapotranspiration can cause desiccation and shrinkage of Arctic wetlands (Liljedahl et al., 2011). The complexity in hydrological interactions implies that different combinations of precipitation and evapotranspiration change directions, in addition to warming, can lead to runoff change in opposite direction to that of precipitation change. That is, precipitation increase (decrease) often can be associated with decreased (increased) runoff into the wetlands and thereby wetland area coverage decrease (increase) (Karlsson et al., 2015). Such hydrological changes can thus alter water balances in nonintuitive ways in relation to precipitation changes, with impacts on wetland systems that depend on the specific local trajectories of hydrological change. Further investigation of such change trajectory details for various parts of the Arctic, however, is outside the overview scope of this review.

Permafrost degradation also can cause expansion or shrinkage of wetland area as indicated in Figure 1 (Jorgenson et al., 2010; Smith et al., 2005; Yoshikawa & Hinzman, 2003). Thermokarst formation, that is, land surface subsidence as a consequence of permafrost thaw, can leads to expansion of lake and pond area (J. Rowland et al., 2010). This involves a reduction in soil strength, by transition into unfrozen conditions, and a reduction in soil volume, due to the lower density of ice compared to water (Murton, 2009). Thermokarst formation has been frequently observed throughout the Arctic in recent years causing increases in wetland area (Farquharson et al., 2019; Fraser et al., 2018; Kokelj & Jorgenson, 2013). Alternatively, permafrost degradation can facilitate drainage of wetlands due to thawing of underlying or adjacent permafrost bodies, including ice wedges (Avis et al., 2011; Liljedahl et al., 2016). Active layer thickening and formation of taliks impact the subsurface hydrology and hydrogeology, increasing lateral and vertical flows

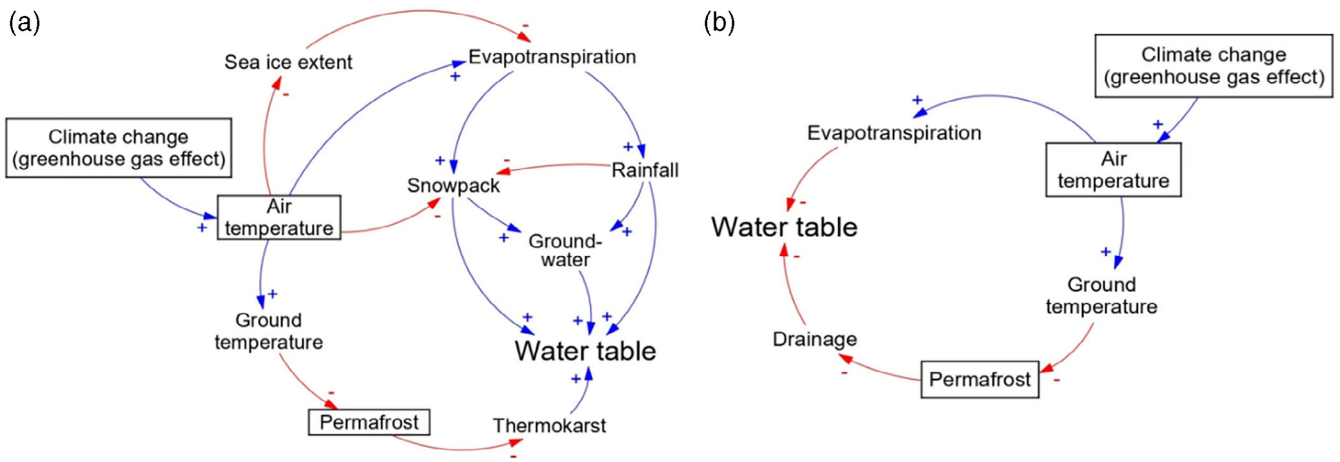

FIGURE 1 Climate-driven processes leading to (a) expansion or (b) shrinkage of wetlands in the Arctic; relevant parameters and their interactions are marked as positive (blue) or negative (red) links. Key considered drivers (boxed) of changes in Arctic wetlands are here hydro-climatic change (including temperature and hydrologic changes) and associated permafrost changes

(Walvoord & Kurylyk, 2016). As these hydrological impacts enhance water connectivity and form new drainage pathways, they can lead to shrinkage of Arctic wetlands (Haynes, Connon, & Quinton, 2018; Yoshikawa & Hinzman, 2003).

Increasing air temperatures, hydrological changes, and thawing permafrost are hence key drivers of changes in Arctic wetland systems (see Figure 1). Smith et al. (2005) found that permafrost distribution is a major influence regarding changes in wetland coverage, as thermokarst processes seem to be more prominent in the continuous permafrost zone, whereas drainage might rather occur in areas of sparser permafrost distribution. Topography is another important parameter, with trends of wetland expansion in Arctic lowlands and decline in Arctic uplands (Jorgenson et al., 2010). However, the future of Arctic wetland systems is overall uncertain, as it also depends on local hydrological and soil conditions and dimension of permafrost and its thaw in combination with the degree and rate of warming (Frampton, Painter, & Destouni, 2013; Frampton, Painter, Lyon, & Destouni, 2011; Selroos et al., 2019). In addition to large-scale warming, it is therefore crucial to also consider a range of local factors, as well as feedback mechanisms, which in combination may reinforce or balance warming effects on permafrost degradation, when assessing the possible future evolution and resilience of Arctic wetlands.

4 | FEEDBACK MECHANISMS IN WETLAND SYSTEMS

4.1 | Surface albedo feedbacks

The albedo is defined as the ratio of radiation that is reflected by a surface on a scale from 0 (black body) to 1 (all radiation is reflected) (Coakley, 2003). Climate-driven shifts in land cover may lead to feedback mechanisms (Figure 2), such as changes in surface albedo modifying the overall energy budget (Budikova, 2009; Winton, 2008), which can reinforce or balance warming in the Arctic and on a global scale. Changes in sea ice extent and snow cover in the Arctic are already leading to drastic changes in surface albedo, particularly in summer, which has experienced high warming in recent decades leading to decline in sea ice extent and delay in sea ice regrowth during autumn (Serreze, Holland, & Stroeve, 2007). This has caused an albedo change ranging from 0.75 for multiyear sea ice to 0.06–0.10 for water bodies, depending on the angle of incoming radiation (Serreze & Barry, 2014). Changes in ice thickness and snow cover on the sea ice further alter the surface albedo (Curry, Schramm, & Ebert, 1995). As a higher fraction of radiation is absorbed instead of reflected, a positive feedback loop develops and reinforces the temperature increase in the Arctic (Winton, 2008). This enhanced warming due to decreased surface albedo of the Arctic Ocean can affect temperatures on adjacent landmasses to up to 1,500 km inland, demonstrating its effect on Arctic wetland systems (Lawrence, Slater, Tomas, Holland, & Deser, 2008; Parmentier et al., 2015). The ice-albedo feedback of the Arctic ocean is also believed to be highly influential for the global climate (Budikova, 2009), with annual radiative forcing averaging 0.1 W m^{-2}

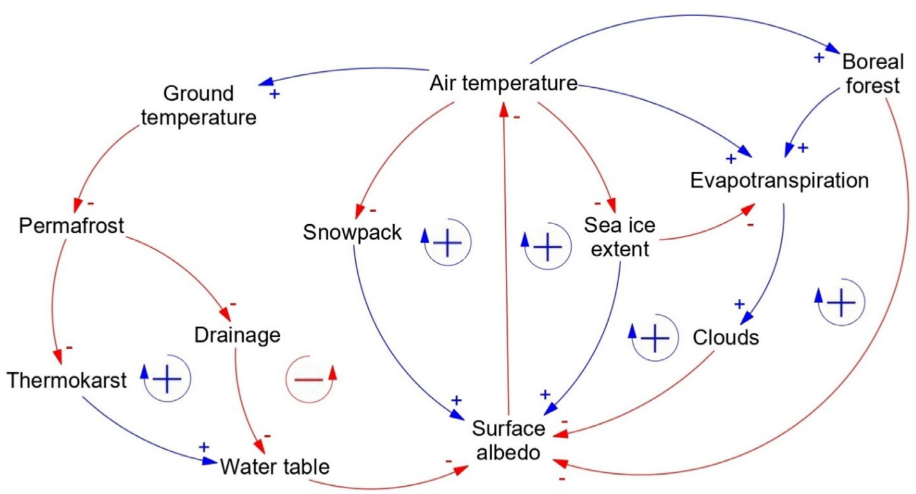

FIGURE 2 Positive (blue) and negative (red) interactions between environmental parameters relevant to Arctic wetland systems and related to surface albedo, which create positive and negative feedback mechanisms (marked with plus and minus signs, respectively) that can reinforce or balance warming

between 1979 and 2007 (Hudson, 2011). Changes in terrestrial snow cover induced by warming and enhanced rainfall include shorter snow cover duration and decreased snowpack thickness (Bintanja & Andry, 2017), which strongly lower the overall surface albedo (Déry & Brown, 2007). Through the reinforcing effect of this feedback, radiative forcing tripled due to changes in Arctic snow cover between 1910–1940 (0.3 W m^{-2} $decade^{-1}$) and 1970–2000 (0.9 W m^{-2} $decade^{-1}$) (Euskirchen, McGuire, & Chapin, 2007). Together with the sea ice-albedo feedback, it is considered to be responsible for the Arctic amplification effect (Serreze & Francis, 2006). Warming-induced vegetation succession, particularly the northward migration of the treeline, also modifies the surface albedo (Frost & Epstein, 2014) and represents another feedback that reinforces warming. A shift in vegetation can decrease surface albedo during summer, ranging from 0.14 to 0.18 for tundra vegetation to 0.09 for dark coniferous trees (Eugster et al., 2000). Furthermore, snow interception by evergreen conifers can lower the winter surface albedo (de Wit et al., 2014). This feedback, however, is estimated to only account for around 3% of warming induced by land cover change, as the spatial extent of vegetation change has been relatively small to date (Chapin et al., 2005). Considering further warming based on future climate scenarios and the time lag effect on vegetation succession, this feedback might become more relevant in the future, although the northward progression of deciduous trees might restore the surface albedo of boreal forests, counteracting this feedback (Eugster et al., 2000). Increases in biomass and decreases in sea ice extent may also enhance evapotranspiration rates and cloud formation which can lower the minimum albedo in vegetated and unvegetated landscapes by up to 0.02, as clouds impede penetration of radiation (Eugster et al., 2000).

Surface albedo is also controlled by terrestrial water surfaces and is hence altered by thermokarst and drainage processes induced by permafrost thaw. An increase in surface water area by expansion of wetlands and formation of thermokarst lakes could lower the surface albedo (Kokelj & Jorgenson, 2013; Runyan & D'Odorico, 2012), causing another positive feedback which reinforces warming. Drainage of wetlands would increase the overall surface albedo, providing a negative feedback that balances warming (Göckede et al., 2019).

4.2 | Feedbacks associated with ground thermal regime

As permafrost is of crucial influence for Arctic wetland systems, feedback mechanisms involving ground temperatures will affect future wetland area (Figure 3). Permafrost itself directly interacts with the thermal regime, as ground freezing increases thermal conductivity, which facilitates penetration of low winter temperatures into the ground, creating a

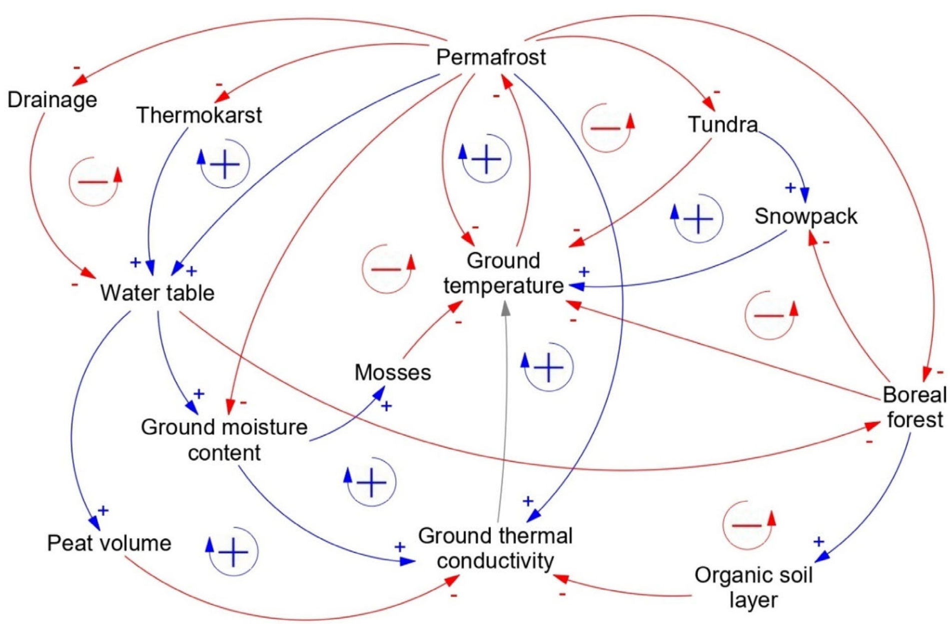

FIGURE 3 Positive (blue) and negative (red) interactions between environmental parameters relevant to the ground thermal regime, which create positive and negative feedback mechanisms (marked with plus and minus signs, respectively) that can reinforce or balance ground temperatures

positive feedback loop (Osterkamp & Romanovsky, 1997). The actual level of thermal conductivity depends on soil type and ice content (Arenson, Colgan, & Marshall, 2015). Degraded permafrost requires less energy for thawing and thus reinforces warming of ground temperatures (Eugster et al., 2000).

Permafrost promotes wetland formation by impeding water percolation, which leads to growth of hydrophilic vegetation and decreases decomposition rates, inducing peat accumulation (M. C. Jones, Grosse, Jones, & Anthony, 2012; van Huissteden, 2020). This insulates the ground from warm summer temperatures and thereby enhances ground freezing, which results in a positive feedback loop and reinforces permafrost formation in wetland environments (Woo & Young, 2003). However, the impacts of peat on ground thermal conductivity are highly dependent on the level of water saturation. Kujala, Seppälä, and Holappa (2008) reported conductivity values of 0.23–0.28 W/mK for dry peat samples and 0.43–0.67 W/mK in frozen dry peat, 0.41–0.50 W/mK for saturated peat, and 1.48–1.49 w/mK for frozen saturated peat. This highlights the dependency on both seasonal conditions and saturation level for this feedback.

Permafrost degradation also creates feedbacks through thermokarst and drainage processes. Inundation caused by thermokarst formation enhances the thermal conductivity of the ground and hence reinforces permafrost thaw (Brouchkov, Fukuda, Fedorov, Konstantinov, & Iwahana, 2004; Quinton et al., 2011). Waterlogged conditions in turn inhibit forest growth and tree survival, which increases the snowpack and its insulating effect on ground temperatures, but reduces the shielding effect of trees (Chasmer, Quinton, Hopkinson, Petrone, & Whittington, 2011; Runyan & D'Odorico, 2012). Therefore, wetland expansion enhances ground temperatures and reinforces permafrost thaw (J. Rowland, Travis, & Wilson, 2011). In contrast, wetland shrinkage through drainage lowers the thermal conductivity of the ground and balances permafrost thaw through negative feedbacks (Briggs et al., 2014; Göckede et al., 2019; Woo, 2012).

All processes leading to enhanced vegetation growth, including drainage, permafrost thaw, increasing air temperatures and higher nutrient availability, influence the ground thermal regime and hence cause feedback loops. These impacts can be direct, for example, shielding the ground from radiation (Blok et al., 2010; Nauta et al., 2015; Runyan & D'Odorico, 2012), or indirect, for example, altering the snowpack (Jorgenson et al., 2010; Myers-Smith & Hik, 2013; Rasmus, Lundell, & Saarinen, 2011; Weintraub & Schimel, 2005), or building up insulating organic soil layers, which can lower ground temperatures by 0.5–0.8°C (Brady & Weil, 2010; Johnson et al., 2013; Rinke, Kuhry, & Dethloff, 2008). Generally, forest expansion leads to negative feedbacks, which prevent or decelerate permafrost thaw, through shielding, interception of snow, and the accumulation of insulating organic matter (Fisher et al., 2016). Disturbances of boreal ecosystems including deforestation, wildfires, and insect outbreaks, can diminish forest growth and therefore accelerate permafrost degradation (Shur & Jorgenson, 2007). Expansion of tundra vegetation, and shrubs in particular, induces positive feedback by trapping snow, which insulates the ground from cold winter temperatures and thereby reinforces permafrost thaw (Nauta et al., 2015). Enhanced growth of mosses by permafrost thaw and inundation acts as insulation for ground temperatures, which balances permafrost degradation (Sim et al., 2019; Turetsky, Mack, Hollingsworth, & Harden, 2010).

4.3 | Spatial variability of environmental changes

The consequences of warming and hydrological changes on environmental systems are not uniform throughout the Arctic but exhibit spatial variation. Table 1 shows the geographic distribution of resulting environmental changes, which have been identified as the most direct and relevant. Certain change trajectories are more widespread, such as permafrost thaw and wildfires, whereas other occur more locally, for example insect outbreaks and lake or wetland drainage. More research is needed on both the spatial and the temporal variations of these change trajectories for different types of wetlands. This should also include determination of relative strengths of interactions, in order to understand dominant feedbacks and net effects resulting from warming and hydrological changes.

5 | CARBON AND ECOSYSTEM DYNAMICS

Arctic wetlands and permafrost soils contain globally relevant carbon stocks (Coffer & Hestir, 2019; Tarnocai et al., 2009), changes of wetland systems can have crucial impacts on the global carbon cycle and hence the greenhouse effect (Figure 4). Enhanced carbon emissions from permafrost degradation are receiving much attention in both science and media (Schuur et al., 2015; van Huissteden, 2020). This positive feedback mechanism involves several

TABLE 1 Direct and relevant consequences of warming and hydrological changes in the Arctic, categorized in permafrost dynamics, snow and sea ice, and ecosystem dynamics, and their geographic distribution

	Consequences of warming	Geographic distribution	References
Permafrost dynamics	Permafrost degradation	Pan-Arctic (1); Subarctic Sweden (2); N Europe (3); Alaska, USA (4); NW Canada (5); N Russia (6)	(1) Biskaborn et al. (2019); (2) Åkerman and Johansson (2008); (3) Harris et al. (2009); (4) Jorgenson, Shur, and Pullman (2006); (5) Quinton et al. (2011); (6) Mazhitova, Malkova (Ananjeva, Chestnykh, and Zamolodchikov (2004)
	Thermokarst formation	Canada (1), including Banks Island (2); Alaska, USA (2); Subarctic Sweden (3)	(1) Farquharson et al. (2019); (2) Fraser et al. (2018); (3) Farquharson, Mann, Grosse, Jones, and Romanovsky (2016); (4) Sannel and Kuhry (2011)
	Lake/wetland drainage	Alaska, USA (1); Old Crow Basin, Yukon, Canada (2); Scotty Creek, Canada (3); Siberia (4)	(1) Yoshikawa and Hinzman (2003); (2) Labrecque, Lacelle, Duguay, Lauriol, and Hawkings (2009); (3) Haynes et al. (2018); (4) Smith et al. (2005)
Snow and sea ice	Reduction in sea ice extent	Arctic Ocean (1)	(1) Stroeve et al. (2012)
	Reduction in snow cover	North America (1); W Russia (2)	(1) Callaghan et al. (2011); (2) Bulygina, Razuvaev, and Korshunova (2009)
Ecosystem dynamics	Vegetation succession	Canada (1); Siberia (2)	(1) Jia, Epstein, and Walker (2009); (2) Frost and Epstein (2014)
	Wildfires	Northern Eurasia (1); including Siberia (2), North Slope of Alaska, USA (3), Canada (4)	(1) Evangeliou et al. (2016); (2) Kharuk et al. (2021); (3) Creamean et al. (2018); (4) Price et al. (2013)
	Insect outbreaks	Subarctic Sweden (1); W North America (2)	(1) Heliasz et al. (2011); (2) Kurz et al. (2008)

environmental processes throughout the Arctic, including decomposition of old undecomposed carbon, release of methane from reservoirs in permafrost soils, and emissions from ecosystems (van Huissteden, 2020). Carbon stored in Arctic wetlands might thus become accessible to decomposition, with waterlogged conditions promoting methane formation (Gedney, Cox, & Huntingford, 2004; Petrescu et al., 2010). As such, expansion of Arctic wetlands can enhance methane emissions, whereas decreases in wetland area may increase emissions of carbon dioxide due to the penetration of oxygen and oxidation of soil carbon as a consequence of drainage (Figure 5) (Avis et al., 2011; Kokelj & Jorgenson, 2013). Regarding future warming, there are concerns of tipping points in temperature increase that, once reached, can lead to independent reinforcing feedbacks (Salvati, Perini, Sabbi, & Bajocco, 2012). This includes the permafrost-carbon-feedback, which would then cause further warming even if anthropogenic emissions were cut completely (Lenton et al., 2019).

Temperature increases in the Arctic are also prolonging the growing season and thus stimulating vegetation growth and succession, which enhances rates of carbon sequestration (Frost & Epstein, 2014; Groendahl, Friborg, & Søgaard, 2007). As waterlogging hampers decomposition, wetlands, particularly peatlands, are important environments for carbon uptake and accumulation in the Arctic (Gallego-Sala et al., 2018). The degree to which the negative feedback of increased carbon sequestration by vegetation (Figure 5) can counteract the permafrost-carbon feedback will ultimately depend on the scale of warming (Bradshaw & Warkentin, 2015; Hayes et al., 2011; W. Zhang, Jansson, Miller, Smith, & Samuelsson, 2014). Determining the net impact of warming on carbon dynamics in Arctic systems hence requires further quantification. Results to date have been inconsistent, indicating both increasing and decreasing carbon sequestration in Arctic wetlands (H. Zhang et al., 2018). Box et al. (2019) point out, based on a modeling approach, that the tundra acted as a carbon sink between 2000 and 2008 due to enhanced primary production, but that this function was reversed from 2008 to 2014, indicating that the positive permafrost-carbon feedback now overweighs the negative one of carbon sequestration by vegetation.

Other processes can also alter carbon sequestration in Arctic wetland systems. Enhanced evapotranspiration under warming may impact primary production negatively, as cloud cover limits incoming shortwave radiation, which is necessary for photosynthesis, and hence carbon sequestration rates may decrease (Mohamed et al., 2004). However, more

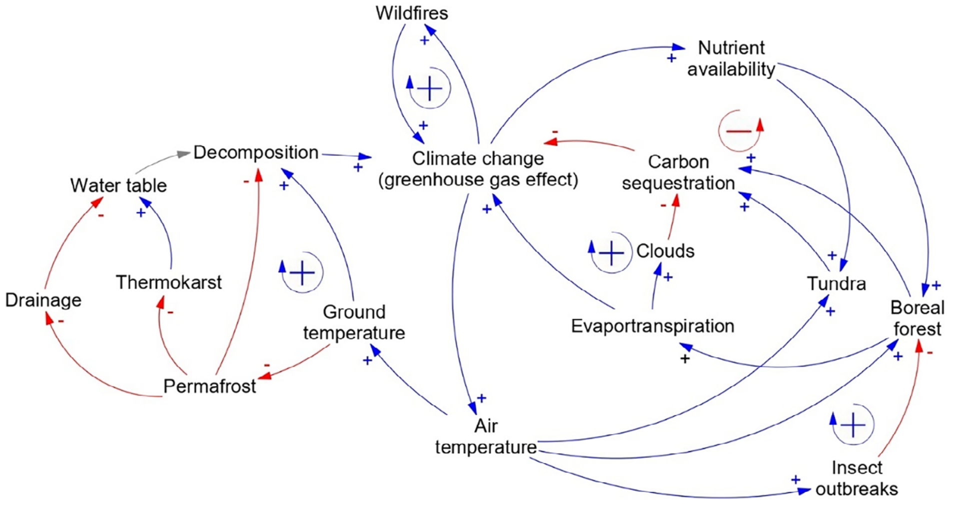

FIGURE 4 Carbon dynamics and positive and negative feedback mechanisms in Arctic wetland systems (marked with blue plus and red minus signs, respectively) including carbon sequestration and emissions under warming as well as enhanced ecosystem disturbances

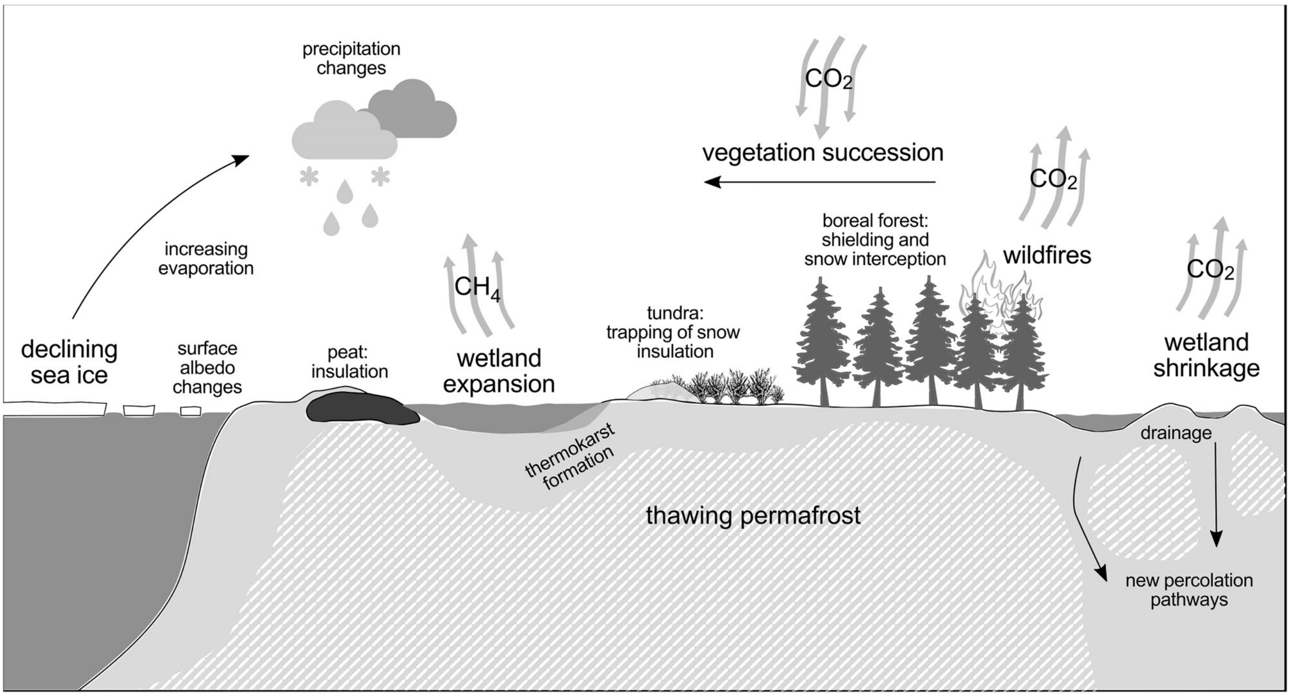

FIGURE 5 Summary of environmental changes in the Arctic caused by warming and their impacts on wetland systems

research is needed to assess the variability of this feedback in space and time (Oliphant et al., 2011; Wang, Prentice, & Davis, 2014).

Moreover, warming and various hydrological changes can enhance the frequency and severity of ecosystem disturbances such as wildfires and insect outbreaks (McGuire et al., 2009). As emissions caused by wildfires contain more than 70% carbon dioxide (Figure 5), a positive feedback to warming evolves (Liu, Goodrick, & Heilman, 2014). Black carbon may also enhance warming in the middle and lower atmosphere and change the surface albedo when deposited on nearby sea ice, glaciers, and ice sheets (Kim, Hatsushika, Muskett, & Yamazaki, 2005; Liu et al., 2014). Fire removes and transforms all forms of organic matter, including vegetation and boreal forests (Macias Fauria & Johnson, 2008; Randerson et al., 2006), organic soil layers (B. M. Jones et al., 2015), and peat (Gibson et al., 2018). However, the long-term net effects of enhanced wildfires on carbon dynamics in the Arctic are still unclear considering the associated creation of more open spaces and increase in nutrient availability that promotes vegetation growth and succession (Lantz, Gergel, & Henry, 2010; Randerson et al., 2006).

Furthermore, insect outbreaks, defined as sudden increases in abundance of a particular species over a short period of time (Singh & Satyanarayana, 2009), have been more frequent in recent years (Heliasz et al., 2011). Insect outbreaks can be initiated by large-scale survival of larvae over winter (Forrest, 2016) and are therefore promoted by warming (Heliasz et al., 2011). Insects in the Arctic feed on vegetation, particularly trees, leading to defoliation and tree mortality (Kurz et al., 2008) and thus diminishing carbon storage in boreal forests (McGuire et al., 2009). Such vegetation changes thus impact carbon dynamics in Arctic wetland landscapes, and can also alter the ground thermal regime, thereby also influencing wetland processes associated with permafrost (Jorgenson et al., 2010; Shur & Jorgenson, 2007).

6 | CONCLUDING REMARKS

Arctic wetlands represent vital ecosystems that are vulnerable to warming-induced and related hydrological changes. The wetlands prevail at and include interfaces between terrestrial and aquatic systems, and are subjected to coupled hydrological, ecological, and permafrost-related influences. Arctic wetlands are therefore complex systems, which complicates projections of their future changes. By applying a systems perspective, different aspects and factors relevant for Arctic wetland systems and their interactions can be assessed. Air temperature, hydrological, and permafrost changes are key factors for the future of these wetland systems, which may include both expansion and shrinkage of wetland area in different parts of the Arctic region. Permafrost thaw may enhance thermokarst formation or wetland drainage. Moreover, changes in Arctic hydrology, through and along with the warming, can also alter the water sources of wetlands, causing either inundation or desiccation of the wetlands.

As wetlands represent important landscapes for carbon cycling and storage, changes in wetland systems also impact the global carbon cycle. Waterlogging lowers decomposition rates, leading to accumulation of organic matter and strengthening the role of Arctic wetlands as carbon sinks. However, permafrost thaw and ecological shifts may increase carbon emissions, adding to the greenhouse effect. Formation of methane is promoted by waterlogging and therefore expansion of wetlands contributes to enhanced methane emissions, whereas wetland drainage might increase emissions of carbon dioxide. Feedback mechanisms that either reinforce or balance warming and permafrost thaw are also highly relevant for both wetland conditions and global climate change. Alterations in surface albedo, resulting from declining sea ice extent, shorter snow cover season, vegetation changes, and modifications in terrestrial water surfaces are important processes reinforcing warming in the Arctic. Thermokarst formation leads to positive feedbacks that reinforce permafrost thaw. Vegetation increase can balance permafrost degradation, by shielding and insulating the ground from incoming radiation and enhances carbon uptake counteracting the positive permafrost-carbon feedback. However, increasing frequency and severity of ecosystem disturbances, such as wildfires and insect outbreaks, may decrease vegetation and impair its carbon sequestration.

Overall, this review elucidates the complexity of Arctic wetland systems and their diverse interactions with warming, hydrological, and other environmental changes. Further research is needed to account for the influences of these various interactions and feedback mechanisms on system structures and dominant interaction dynamics in improved quantification and projection of net climate change effects and future evolution of the Arctic wetland environments.

ACKNOWLEDGMENT

This study was funded by the Swedish Research Council Formas [grant number 2017-00608], Arctic Avenue and ASIAQ mobility grants from Stockholm University.

AUTHOR CONTRIBUTIONS

Hanna N. Kreplin: Conceptualization; formal analysis; investigation; methodology; writing-original draft. **Carla Sofia Santos Ferreira:** Project administration; writing-review & editing. **Georgia Destouni:** Writing-review & editing. **Saskia D. Keesstra:** Writing-review & editing. **Luca Salvati:** Writing-review & editing. **Zahra Kalantari:** Project administration; writing-review & editing.

DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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How to cite this article: Kreplin HN, Santos Ferreira CS, Destouni G, Keesstra SD, Salvati L, Kalantari Z. Arctic wetland system dynamics under climate warming. *WIREs Water*. 2021;8:e1526. https://doi.org/10.1002/wat2.1526