Pathways for Ecological Change in Canadian High Arctic Wetlands Under Rapid Twentieth Century Warming

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Pathways for ecological change in Canadian High Arctic wetlands under rapid twentieth century warming

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Key Points:

- The ecological, hydrological and C accumulation responses of Arctic wetlands to climate warming may be strongly influenced by wetland type;
- Contrasting site-specific responses to an increase in growing degree days include increased moss diversity and a shift to shrub-dominance;
- Intensive grazing from Arctic geese may be an important driver for recent vegetation change in High Arctic coastal wetlands.

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Abstract

We use paleoecological techniques to investigate how Canadian High Arctic wetlands responded to a mid-twentieth century increase in growing degree days (GDD_0). We observe an increase in wetness, moss diversity and carbon accumulation in a polygon mire trough, likely related to ice-wedge thaw. Contrastingly, the raised center of the polygon mire showed no clear response. Wet and dry-indicator testate amoebae increased concomitantly in a valley fen, possibly relating to greater inundation from snowmelt followed by increasing evapotranspiration. This occurred alongside the appearance of generalist hummock mosses. A coastal fen underwent a shift from sedge to shrub-dominance. The valley and coastal fens transitioned from minerogenic to organic-rich wetlands prior to the GDD_0 increase. A subsequent shift to moss-dominance in the coastal fen may relate to intensive grazing from Arctic geese. Our findings highlight the complex response of Arctic wetlands to warming and have implications for understanding their future carbon sink potential.

Plain Language Summary

The response of Arctic wetland ecosystems and carbon stores to climate change is uncertain. We investigate the response of wetland ecosystems in the Canadian High Arctic to twentieth century climate warming. We use proxies for changes in vegetation (plant macrofossils) and wetness (testate amoebae) preserved in the wetland soil in combination with radiocarbon dating to reconstruct the past ecology of these wetlands. This approach allows us to explore beyond the timeframe of monitoring studies. Our results suggest that wetland type is an important determinant of the response of ecological, hydrological and soil carbon accumulation to climate warming. Our findings highlight the clear, but complex response of Arctic wetlands to twentieth century warming. This has important implications for understanding the future carbon sink potential of these ecosystems.

Keywords

Permafrost Peatlands; Climate Change; Growing Degree Days; Testate Amoebae; Shrubification; Arctic Geese Grazing.

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1 Introduction

Climate warming over the last century has been greatest in the Arctic and is projected to continue in the twenty-first century at a rate above the global average [*Christensen et al.*, 2013]. Arctic warming is causing widespread permafrost thaw [*Jorgenson et al.*, 2006; *Payette et al.*, 2004] and alteration of terrestrial ecosystem hydrology [*Smith et al.*, 2007], vegetation [*Myers-Smith et al.*, 2011] and wildfire regimes [*Gibson et al.*, 2018; *Myers-Smith et al.*, 2008]. Changes to high-latitude ecosystems are likely to influence their carbon budgets, including global warming through enhanced carbon emissions [*Dorrepaal et al.*, 2009]. Permafrost soils in general could become carbon sources with warming through greater aerobic (CO_2) and anaerobic (CH_4) decomposition rates [*Natali et al.*, 2015; *Schuur et al.*, 2015]. However, longer, warmer growing seasons and changes in Arctic precipitation regimes [*Bintanja & Selten*, 2014; *Kattsov et al.*, 2007; *Kopec et al.*, 2016] may stimulate carbon capture through enhanced plant productivity in peatlands, and the transition of minerotrophic wetlands into organic peatlands [*Charman et al.*, 2013; 2015; *Gallego-Sala et al.*, 2018; *Morris et al.*, 2018]. Recent evidence shows an inconsistent response of Arctic and sub-Arctic peatlands to warming in terms of carbon accumulation [*Zhang et al.*, 2018a].

In the Arctic, wetlands occupy ~8% of the non-glaciated land area [*Walker et al.*, 2005] and – although high-latitude carbon stocks are poorly constrained – wetlands store a disproportionate amount of carbon for their extent [*Tarnocai et al.*, 2009]. Arctic wetlands exemplify the complexity of landscapes underlain by permafrost and typically occur in three locales: on ground affected by ice-wedge formations (polygon mires); on previously-glaciated terrain with favorable topographic depressions (known as patchy wetlands); and in coastal zones of isostatic uplift (coastal wetlands) [*Glenn & Woo*, 1997; *Woo & Young*, 2006]. Across Arctic wetlands, warming has been linked to greater plant biomass [*Hill & Henry*, 2011], vegetation composition changes and desiccation [*Woo & Young*, 2006, 2014; *Zhang et al.*, 2018b]. Ice-wedge polygon mires specifically are complex and dynamic systems [*de Klerk et al.*, 2011; *Fritz et al.*, 2016], and degradation in response to recent warming has led to changes in vegetation and drainage [*Fraser et al.*, 2018; *Jorgenson et al.*, 2015; *Liljedahl et al.*, 2016; *Perreault et al.*, 2017]. Similarly, vegetation in some sub-Arctic and Arctic coastal wetlands has been altered by increasing bird grazing pressures in recent decades [*Jefferies & Rockwell*, 2002; *Peterson et al.*, 2013].

Future hydrological changes, vegetation shifts and degradation of permafrost have been identified as key areas of uncertainty in the prediction of permafrost carbon dynamics [*Abbott et al.*, 2016]. There is limited information on the response of Arctic wetlands to climate change and their potential to transition into productive peatlands on centennial timescales. For the first time in the Canadian High Arctic, we use a high-resolution paleoecological approach (testate amoebae and plant macrofossils) to reconstruct past moisture conditions and vegetation histories in peat-forming wetlands. We aim to investigate the ecological response to twentieth century climate warming in the three main types of High Arctic wetland: (i) a polygon mire; (ii) a valley fen (a type of patchy wetland); and (iii) a coastal fen.

2 Study sites, materials and method

The study region is in the continuous permafrost zone of the western Canadian Arctic tundra, between the latitudes 68.5 and 74.5°N [Figure 1]. We study two wetlands on northern Banks Island, Northwest Territories: a polygon mire (74.459°N, 121.04°E) and a valley fen (74.05°N, 118.429°E). The distinctive topography of the polygon mire was captured by extracting a monolith from a raised center mound and from a surrounding trough. Our third

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site is a coastal fen (68.65°N, 105.455°E) located on an island ~50 km south of Cambridge Bay, Nunavut, where two monoliths <10 m apart were collected as replicate paleo-records.

Monoliths were sampled to the base of the active layer and subsampled in the laboratory at 1–cm depth intervals. Bulk density and organic matter content were calculated in accordance with *Chambers et al.* [2011]. Testate amoebae were prepared for analysis using the method outlined by *Booth et al.* [2010]. In the absence of an appropriate transfer function, testate amoebae were grouped into categories of hydrological preference based on a detailed literature review (Table S2). Plant macrofossils were prepared in accordance with *Gałka, et al.* [2017a]. Above-ground plant macrofossils and bulk peat (where reliable plant macrofossils were not present) were radiocarbon dated (Table S1). Radiocarbon dates were calibrated using Clam 2.2 [*Blaauw*, 2010] in R 3.4.3 [*R Core Team*, 2018]. The IntCal13 [*Reimer et al.*, 2013] calibration curve for pre-bomb dates and *Hua et al.* [2013] for post-bomb dates were used. When post-bomb dates demonstrated multiple probability distributions during calibration, we applied the principle of superposition to determine the most likely probability distribution. Chronological uncertainty can be introduced by cryoturbation in permafrost soils, particularly towards to base of the active layer [*Bockheim & Tarnocai*, 1998; *Ping et al.*, 2008]. These factors are considered in our interpretation and are comprehensively discussed in the supplementary materials (Table S1 and Text S3). The most appropriate age-depth model for each chronology was selected including linear interpolation, cubic spline and polynomial regression. Growing degree days above 0°C (GDD_0) were calculated for each site from monthly climate re-analysis data spanning the period AD 1851–2011 [*Compo et al.*, 2011]. Changepoint analysis [*Killick & Eckley*, 2014] was conducted in R 3.4.3 [*R Core Team*, 2018] on GDD_0 time series data for each site. See full methods and study site information in supplementary material [Figures S1 to S6; Tables S1 to S2; Text S1 to S3].

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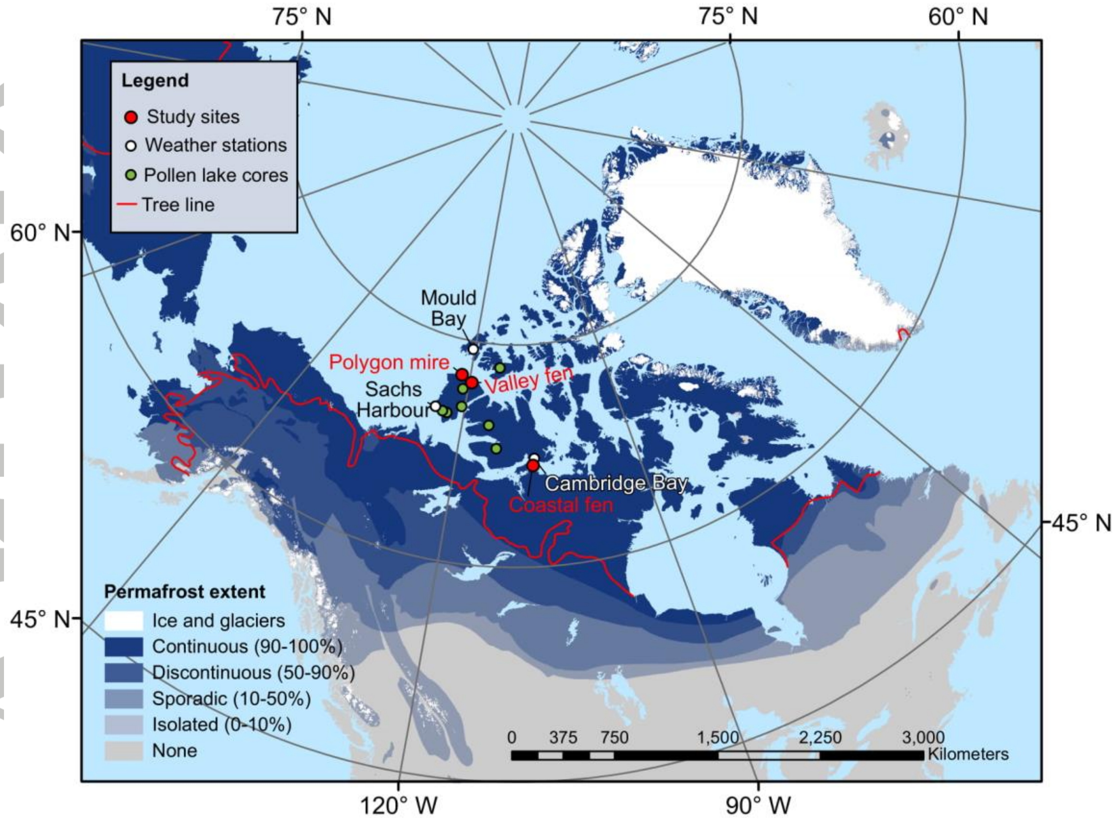

Figure 1. Study sites, nearby weather stations and lake cores used for pollen-based temperature reconstruction [*Gajewski*, 2015]. Permafrost and the tree line data from *Brown et al.* [2002].

3 Results

3.1 Twentieth century warming and lengthening growing seasons in the western Arctic

In the western Arctic following a warm period from ~10–7.5 Ka BP there was general cooling throughout the Holocene [*Gajewski*, 2015; Figure 2c]. Weather station records beginning ~AD 1950 document twentieth century climatic warming near to our sites [Figure 1], and across the Arctic [*Hassol et al.*, 2004]. The Cambridge Bay and Sachs Harbour stations show pronounced warming rates of 0.3°C per decade and 0.5°C per decade respectively, contrasted to 0.1°C per decade at Mould Bay, the highest latitude station [Figure 2a]. Re-analysis data [*Compo et al.*, 2011] demonstrated a pronounced increase in GDD_0 across all wetland sites with changepoints detected between 1931 and 1940 [Figure 2b]. Following respective changepoints, mean GDD_0 at the polygon mire increased from 49 ± 50 °C days yr^{-1} to 152 ± 46 °C days yr^{-1} (changepoint: 1940) and at the valley fen, from 105 ± 76 to 260 ± 6 °C days yr^{-1} (changepoint: 1936) (error terms indicate standard deviation). After the 1931 changepoint, mean GDD_0 at the coastal fen increased from 400 ± 132 to 605 ± 68.3 °C days yr^{-1}.

The rise in GDD_0 in the 1930s [Figure 2b] is consistent with a well-documented climatic fluctuation (~1920-1940) around the North Atlantic. This event began in the 1920s and resulted in positive Arctic-wide average temperature anomalies for most of the 1930s

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[*Johannessen et al.*, 2004; *Polyakov et al.*, 2003]. Causes of the climatic fluctuation remain open to debate, with internal atmospheric variability, anthropogenic greenhouse gas forcing, solar variability, volcanic forcing and regional dynamic feedbacks proposed in the literature [*Wood & Overland*, 2010]. *Bengtsson et al.* [2004] suggested natural variability was the likely cause, as reduced sea ice cover was critical in initiating warming of ~1.7°C during the peak period between 1930 and 1940 at 60-90°N. However, *Wood & Overland* [2010] interpreted the event as an intrinsically-forced albeit essentially random climatic phenomenon, superimposed on rising temperatures associated with anthropogenic forcing. GDD_0 have remained high following this event [Figure 2b] and increased elsewhere in the Canadian High Arctic in the past few decades [*Woo & Young*, 2014].

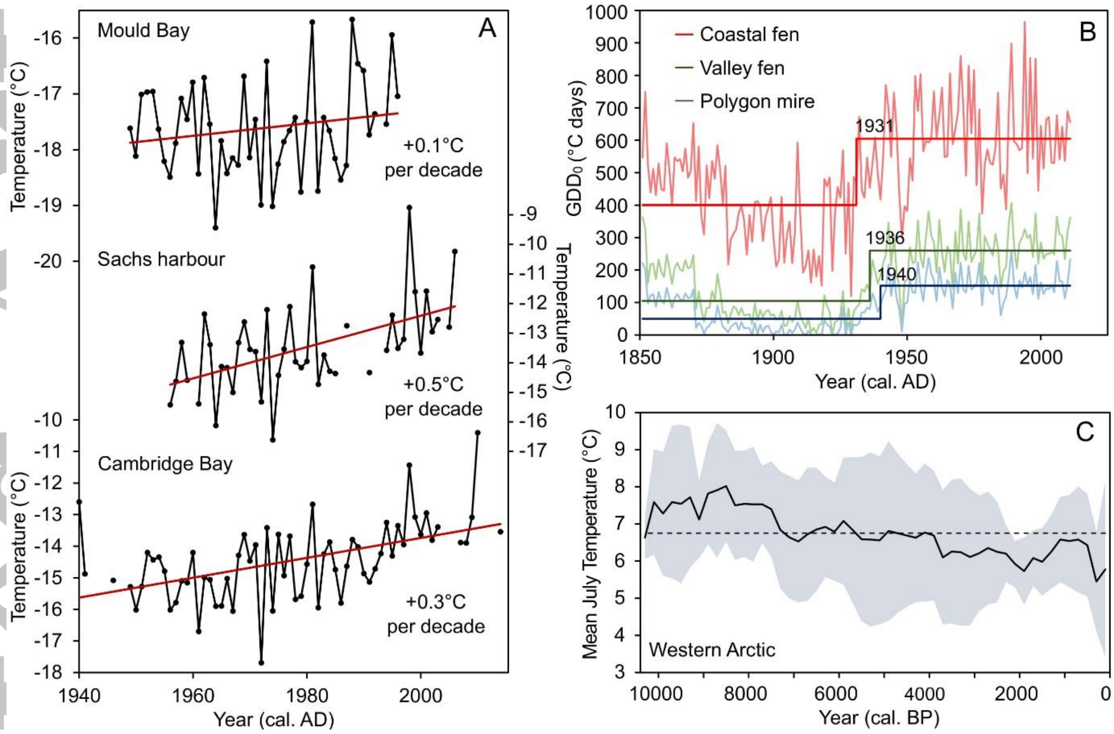

Figure 2. Recent warming in western Canadian Arctic. **a**) Annual temperature data from nearby weather stations. **b**) GDD_0 modelled for each site from climate re-analysis data [*Compo et al.*, 2011]. Stepped lines indicate changepoints. **c**) Reconstructed mean July temperature for western Arctic during the Holocene [*Gajewski*, 2015]. Shading indicates one standard deviation.

3.2 Paleoecological results

3.2.1 Polygon mire

The polygon mire demonstrates contrasting responses to recent warming between the raised center and the trough. The raised center monolith [11 cm; Figure 3a] is mainly composed of partially-decomposed *Scorpodium cossonii* (80–90.5%), bulk density is relatively high (0.36 ± 0.1 g cm^{-3}), while organic matter is relatively low (29.8 ± 9.4%), and carbon accumulation increases towards the top of the profile. The trough monolith [17 cm; Figure 3b] is more dynamic by comparison, recording multiple vegetation shifts. The lower phase (17–7 cm) consists of a light-brown, peaty soil undergoing a gradual transition (~AD 750–1800) from *S. cossonii* (40-85%) and *Warnstorfia sarmentosa* (0–35%) moss to a more

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sedge (Cyperaceae) and herb-dominated wetland. During this phase carbon accumulation is low (6.2 ± 2.1 g m^{-2} yr^{-1}), organic matter is low (27.8 ± 8.7%) and there is relatively high bulk density (0.51 ± 0.16 g cm^{-3}). In the upper phase (0–7 cm) organic matter increases (max: 77.4%) and bulk density decreases (min: 0.04 g cm^{-3}). A sedge and herb-dominated ecosystem is present from ~AD 1800 before an increase in moss diversity at ~AD 2000, including the presence of *S. cossonii* (20–70%), *Calliergon* spp. (10–30%) and *Campylium* cf. *stellatum* (10–20%). Coincident with this ~AD 2000 is a shift in hydrological conditions, with wet-indicator testate amoeba taxa increasing dramatically (68.8 ± 17.9%) and carbon accumulation increasing to between 45.7–102.8 g m^{-2} yr^{-1}.

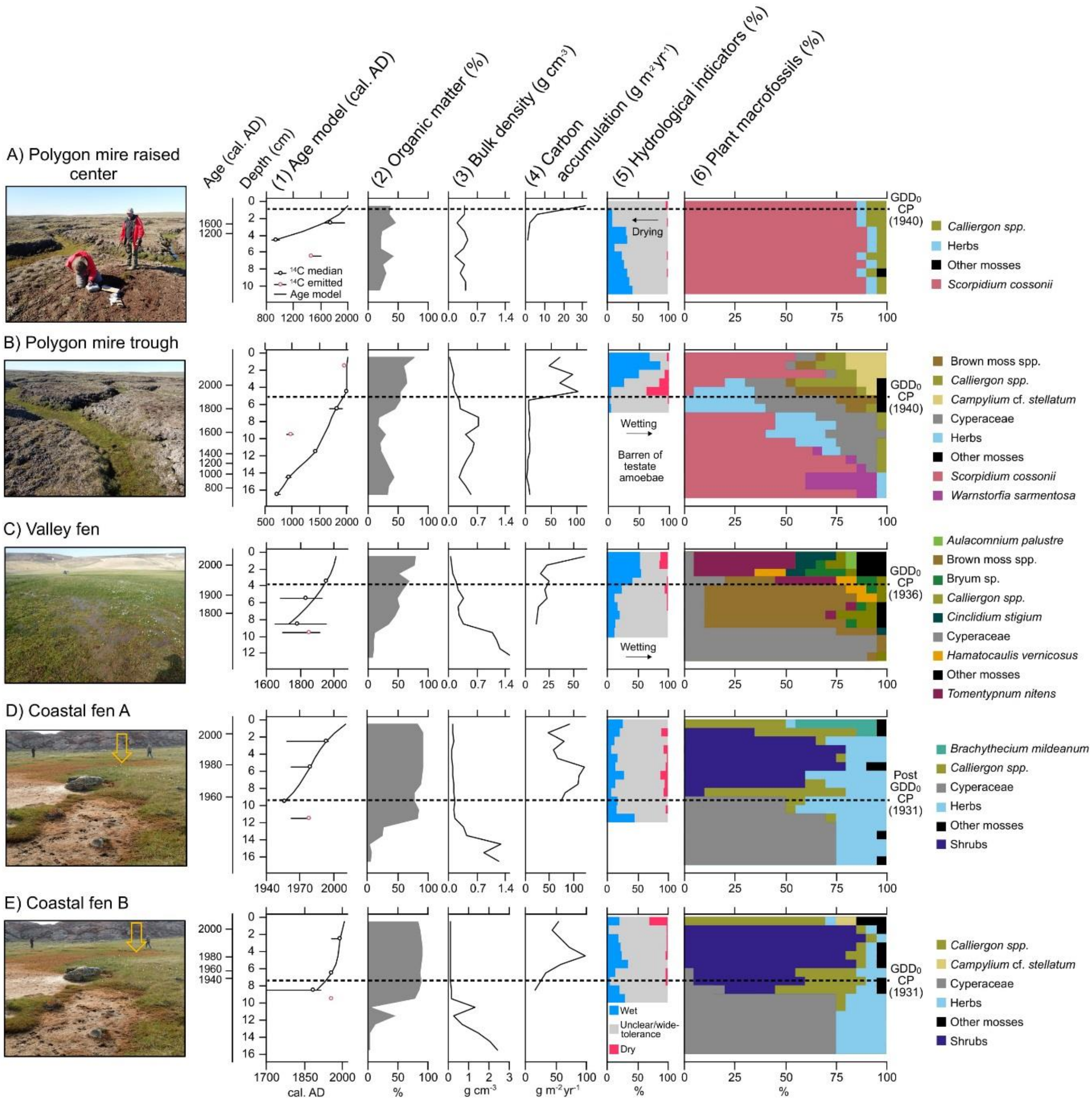

Figure 3. Summary stratigraphic diagram of paleoecological variables from polygon mire raised center (**a**), polygon mire trough (**b**), valley fen (**c**) and coastal fen (**d** and **e**; yellow arrows indicate sampling locations). GDD_0 CP is changepoint in GDD_0. For detailed stratigraphic diagrams see Figures S7-S21.

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3.2.2 Valley fen

The valley fen monolith [13 cm; Figure 3c] is composed of three main phases. Notwithstanding chronological uncertainty, our age-depth model suggests that the base of the record (13–9 cm) accumulated before ~AD 1780. The base phase is characterized by a pale-colored mineral layer of low organic matter content (7.2–11.6%), high bulk density (1.08–1.52 g cm^{-3}) and sedge-dominated vegetation (>75%). At ~7 cm (~AD 1800) there is a sharp increase in organic matter (11.6–33.4%) and a decrease in bulk density (1.08–0.38 g cm^{-3}). Throughout the middle section of the profile (9–4 cm) there is a gradual increase in organic matter to 56.5% and decrease in bulk density to 0.23 g cm^{-3} (~AD 1950). This change represents the development of a more productive intermediate or rich fen system dominated by Brown moss spp. (60-–75%), *Calliergon* spp. (<20%) and *Hamatocaulis vernicosus* (<10%), with increasing carbon accumulation (10.9–20.1 g m^{-2} yr^{-1}). In the top 4 cm (~AD 1950 onwards), the wetland demonstrates properties more characteristic of a peatland. Organic matter continues to increase to 78.8% and bulk density decreases further to 0.06 g cm^{-3}. *Tomentypnum nitens* (30–50%), *Cinclidium stygium* (0–20%) now dominate the valley fen record alongside other mosses. These mosses (including *T. nitens* and *C. stygium*) may have been present under the Brown moss spp. classification, however decomposition made species identification impossible.

3.2.3 Coastal fen

The peat monoliths analyzed from coastal fen A (CFA) and coastal fen B (CFB) demonstrate highly similar responses, each recording two distinct phases [Figure 3d and 3e]. Notwithstanding chronological uncertainty, our age-depth model suggests the lower phase (CFA 17–12 cm, CFB 16–10 cm) accumulated before ~AD 1950. This lower phase is characterized by a pale-colored minerogenic layer dominated by sedges and herbs, with low organic matter (mostly 2–26%), and a high bulk density (max: 2.44 g cm^{-3}), which decreases up the succession (min: 0.38 g cm^{-3}). The upper phase (CFA 12–0 cm, CFB 10–0 cm) is characterized by a darker-colored peaty layer of poorly-decomposed plant material and a sharp rise in organic matter that remains consistently high (average of upper phases in both monoliths = 87 ± 4.8%) alongside a relatively low bulk density (average of upper phases in both monoliths = 0.12 ± 0.02 g cm^{-3}). The vegetation in the upper phase initially changes from sedge and herb-dominance, to a transitional phase dominated by the moss *Calliergon richardsonii* (CFA 9–8 cm, CFB 9–8 cm). Shrubs then dominate (CFA 8–2 cm, CFB 8–1 cm), before a return to a dominance of *C. richardsonii* (>50%) alongside the appearance of *Brachythecium mildeanum* (in CFA) (<40%). At the coastal fen site, the ecosystem shift to shrub-dominance is coincident with fast carbon accumulation rates (~AD 1980) of >100 g m^{-2} yr^{-1}.

4 Discussion

Under twenty-first century warming and in the presence of adequate moisture, Arctic wetlands such as our study sites may become more productive and transition into peatlands – this could to some extent mitigate carbon losses from degrading peatlands further south [*Charman et al.*, 2015; *Gallego-Sala et al.*, 2018]. The Arctic wetlands we studied did demonstrate ecological responses to a mid-twentieth century increase in GDD_0. However, the pathway of these responses varied between wetland types and therefore their future carbon balance is likely to be complex and may vary between wetland types. In particular, our results highlight the importance of ground-ice dynamics, changing seasonal hydrological regimes and herbivory.

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Ground-ice dynamics and permafrost feedbacks:

Ground-ice dynamics and feedbacks in permafrost regions are a key uncertainty in understanding the carbon cycling response of these systems to warming [*Grosse et al.*, 2016; *Schuur et al.*, 2015]. We believe our polygon mire site exemplifies the influence ground-ice dynamics can have upon wetland structure and ecology with warming. A changepoint increase in GDD_0 was detected at the polygon mire in 1940 [Figure 2b]. A further increase in GDD_0 from 1956–2016 at Sach Harbour has been documented and linked to increasing active layer depth [*Fraser et al.*, 2018]. At the polygon mire, the raised center monolith showed no response to recent warming, perhaps because permafrost thaw has not yet induced the collapse of the raised center structure, as may be the case in some Siberian peatlands (c.f. *Teltewskoi et al.*, 2016]. In contrast, the trough demonstrates high sedge abundance from ~AD 1800, consistent with stable or initially degrading ice-wedges, while the shift to dominance of hydrophilic moss (*S. cossonii*) from ~AD 2000, is characteristic of advanced ice-wedge degradation [Figure 3.6b; *Jorgenson et al.*, 2015]. Recent ice-wedge degradation is further supported by an increase in wet-indicator testate amoeba from ~AD 2000 [Figure 3.5b]. This decadal or sub-decadal timescale of trough wetting is supported by observations from across the Arctic since the mid-twentieth century [*Fraser et al.*, 2018; *Jorgensen et al.*, 2015; *Liljedahl et al.*, 2016]. The previous periods of sedge and herb-dominance and moss-dominance in the record [Figure 3.6b] may relate to previous ice-wedge degradation and stabilization cycles. However, accurate interpretation of these previous trough vegetation shifts is limited by the absence of a testate amoeba hydrological record (barren below 7 cm). Local geomorphological and autogenic vegetation processes are key in the formation and variability of polygon mires, but climate change may modify these patterns [*Ellis & Rochefort, 2004*]. We suggest the magnitude of recent warming [Figure 2] alongside background autogenic processes caused a threshold of ice-wedge thaw to be reached ~AD 2000 in the polygon mire.

Under advanced ice-wedge degradation and the establishment of hydrological connectivity between troughs, landscape-scale drainage can be initiated [*Liljedahl et al.*, 2016]. Drainage could threaten wetland persistence and expose partially-decomposed carbon to increased aerobic decomposition – elevating CO_2 emissions [*Schädel et al.*, 2016]. However, the establishment of moss vegetation ~AD 2000, under wetter conditions [Figure 3b], may represent a negative ecological feedback to ice-wedge thaw in troughs. The accumulated layer of moss since ~AD 2000 may act as an insulating layer alongside slumped material from trough banks to retard further thaw [*Jorgenson et al.*, 2006; 2015]. The slumping process was observed onsite [Figure S2] and may explain an older bulk peat date (1–2 cm; AD 1956 ± 1) stratigraphically above a reliable plant macrofossil date (4–5 cm; AD 1998 ± 2; Table S1). The negative ecological and geomorphological (slumping) feedbacks could contribute to the deceleration of ice-wedge degradation. Our results highlight the importance of ground-ice dynamics and autogenic factors in polygon mires with warming [c.f. *Fritz et al.*, 2016; *Vardy et al.*, 2005].

Changing hydrological regime and precipitation with warming:

The short growing season of around two months in the High Arctic creates a highly seasonal hydrological regime, which our results suggest is being influenced by warming. When temperatures rise above 0°C there is an influx of water to catchments from the thaw of ground-ice and snowbanks that have accumulated over the winter [*Glenn & Woo*, 1997] – this is particularly relevant at our valley fen site. An increase in GDD_0 at the valley fen from AD 1936 [Figure 2b] is followed at ~AD 1950 by a marked increase in wet-indicator testate amoeba taxa and slight increase in dry-indicator taxa [Figure 3.5c]. The apparent increase in

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wetness is likely as a result of increased catchment thaw under warming conditions – a process that has been observed in other Arctic and alpine regions [*Fontana et al.*, 2010; *Woo & Young*, 2014]. The increase in dry-indicator testate amoeba taxa may represent increasingly dry conditions towards the end of the growing season as a result of increased evapotranspiration over a longer and warmer summer [*Oechel et al.*, 1998; *Woo & Young*, 2014; *Zhang et al.*, 2018b]. This increased variability in hydrological conditions from ~AD 1950 is further supported by the presence of the hummock mosses *T. nitens* (30–50%) and *Aulacomnium palustre* (<5%). These mosses have broad climatic and ecological ranges [*Minke et al.*, 2009; *Nicholson & Gignac*, 1995] making them suitable for the increasingly variable moisture conditions. *T. nitens* specifically has been observed in both wet High Arctic [*Steere & Scotter*, 1979] and dry Boreal fens [*Gignac et al.*, 1991], suggesting a certain resilience to warming temperatures alongside more variable hydrology.

Under the likely scenario of further Arctic warming [*Christensen et al.*, 2013], alterations to the hydrology of the valley fen may threaten future persistence. Greater summer snowmelt may increase inundation in the short term. However, there may come a point where snowbanks become sufficiently depleted by increased evapotranspiration and no longer have the capacity to sustain wetlands [*Woo & Young*, 2006]. Possible increases in twenty-first century Arctic late-autumn and winter precipitation [*Bintanja & Selten*, 2014; *Kattsov et al.*, 2007] may counteract increased evaporative losses to some extent. However, large uncertainties remain in predicting future precipitation patterns. Since ~AD 1950 there has been no clear shift in precipitation at the closest weather stations to our sites [Figure S1]. Furthermore, increased future permafrost thaw and active layer thickening could increase permeability and thus drainage [*Avis et al.*, 2011]. Under the scenario of drying, CO_2 emissions from aerobic decomposition are likely to increase and the wetland may become a carbon source [*Oechel et al.*, 1998]. Carbon accumulation rates since ~AD 1950 remain consistent around 20 g m^{-2} yr^{-1} before a recent increase to 61.3 g m^{-2} yr^{-1} [Figure 3.4c]. This increase hints at improved productivity with increased GDD_0, indicating that the wetland ecosystem has not reached a moisture-limited point where carbon loss to decomposition outweighs input from litter. However, this carbon accumulation rate should be treated with caution because incomplete decomposition of recently accumulated organic matter was not accounted for. Our results demonstrate a clear ecosystem shift in response to recent warming, linked to a changing hydrological regime. The balance of possible increases in twenty-first century precipitation against summer evapotranspiration losses - alongside potential changes to drainage with permafrost thaw - are likely to determine the future sustainability and carbon accumulation capacity of this valley fen and potentially similar Arctic wetlands.

Potential impact of herbivory on Arctic coastal wetlands:

The timing and magnitude of the ecosystem shift from sedges to shrubs is well established in both coastal fen records by ~AD 1950 and is likely linked to warming. The subsequent shift to moss dominance in both records since ~AD 2000 is likely linked to changes in avian grazing pressures. The increased dominance of shrubs in this coastal wetland ~AD 1950 follows an increase in GDD_0 at AD 1931 [Figure 2b]. Northward expansion of shrub communities and increased productivity in response to recent warming has been widely documented across the tundra [*Elmendorf et al.*, 2012; *Myers-Smith et al.*, 2011; *Tape et al.*, 2006] and directly linked to increased shrub and decreased sedge abundance in an Alaskan coastal wetland [*Carlson et al.*, 2018]. Isostatic uplift can lead to a drop in relative sea-level and lowering of the water table, increasing dryness to facilitate sedge to shrub succession [*Klinger & Short*, 1996]. However, any hydrological shift associated with an increased abundance of shrubs is unclear in our testate amoeba data.

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Furthermore, the projected range of sea-level change for nearby Cambridge Bay by 2100 relative to 2010 is between a 15 cm fall and 30 cm rise, depending upon future emissions scenarios [*James et al.*, 2011]. Therefore, isostatic uplift is likely to be more relevant in regions where uplift outpaces global eustasy, such as Hudson Bay and the Northwest Passage [*James et al.*, 2015]. We suggest the increase in GDD_0 is the most plausible mechanism driving this shift to shrub-dominance at our site. The role of climate is further supported by evidence of a recent increase in shrub taxa in sub-Arctic permafrost peatlands in Sweden [*Gałka, et al.*, 2017b] and Alaska [*Gałka et al.*, 2018] - areas of limited isostatic uplift [*Geruo et al.*, 2013; *Peltier*, 2004].

The contemporary wetland ecosystem demonstrates minimal shrub cover and contains large sections of bare substrate and patches of dead moss [Figure S4]. Both coastal fen monoliths demonstrate a recent shift to mosses ~AD 2000 [Figure 3d and 3e]. Wildfire has reduced shrub cover in similar environments [*Higuera et al.*, 2008; *Mack et al.*, 2011], but the absence of macro-charcoal at our site rules this out. An alternative possibility for the reappearance of moss is increased grazing by Arctic geese, e.g. lesser snow geese (*Chen caerulescen*) and Ross's geese (*Anser rossi*). Snow geese have demonstrated a preference for herbivory of vascular plants and therefore across the coastal wetlands of northern Canada, areas that have been subjected to destructive grazing often experience an increase in moss vegetation abundance [*Abraham & Jefferies*, 1997; *Alisauskas et al.*, 2006]. In areas of more intense grazing, replacement of moss by bare peat has been documented [*Conkin & Alisauskas*, 2017]. Similarly, the recolonization of mosses towards the edge of the wetland [Figure S4] is typical of disturbed wetlands [*Speed et al.*, 2010].

Arctic geese populations are being driven up by improved food availability from agricultural production (via artificial fertilizers and subsidy policies) in the wintering grounds of the southern United States [*Fox et al.*, 2005; *Jefferies et al.*, 2004]. Our coastal fen site is located ~20 km northwest of Queen Maud Gulf Migratory Bird Sanctuary (QMBS), a major summer nesting site for Arctic geese [*Cooch et al.*, 2001] and bird presence can be confirmed unambiguously at our coastal fen site by an abundance of tracks and excrement [Figure S4]. The QMBS has seen Arctic geese nesting populations rise from ~44,300 in 1965 to ~2,251,900 in 2006, with over 50% of this increase occurring since 1998 [*Kerbes et al.*, 2014]. The likely recent intensification of grazing in established summer nesting sites may have caused snow geese to seek out more pristine habitats further north as they warm, such as our site, and begin to degrade them. Therefore, we suggest either edge recolonization following snow geese disturbance or selective snow geese herbivory provides a plausible explanation for the dramatic shift from a shrub to moss-dominated ecosystem ~AD 2000. It remains unclear what implications this shift from shrub to moss-dominance will have upon long-term carbon accumulation rates, however our findings highlight the potential importance of avian grazing (substantially influenced by non-climate factors) in the context of future Arctic carbon cycling.

5 Conclusions

Warming of the western Canadian Arctic has caused a mid-twentieth century increase in growing degree days above 0°C (GDD_0). In the absence of long-term monitoring data our high-resolution multiproxy paleoecological approach – the first of its kind in the Canadian High Arctic – allowed us to identify alternate pathways for ecological responses to recent warming in three wetlands. The main findings of our study are:

1) An increase in moss diversity, decrease in sedges and herbs, and an increase in carbon accumulation rate occurred in the trough of a high centered polygon mire following the shift

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in GDD_0. Testate amoeba data suggest increased wetness at this time which may be related to ice-wedge thaw driven by recent climate warming. In comparison, the raised center of the polygon mire showed no clear response to recent warming.

2) In a valley fen, the appearance of generalist mosses coincides with the shift in GDD_0. This occurs alongside an increase in both dry- and wet-indicator testate amoebae that may suggest increased seasonality in hydrological conditions (wetter conditions during snowmelt, and drier conditions in the late summer owing to increased evapotranspiration). This site shifted from a minerogenic to an organic-rich wetland sometime prior to the shift in GDD_0.

3) A coastal fen site experienced an ecosystem shift coincident with an increase in GDD_0 from a sedge-dominated fen to a shrub-dominated fen with a high carbon accumulation rate. This site shifted from a minerogenic wetland to an organic-rich peatland sometime before the shift in GDD_0. The results from this site have important implications for understanding the expansion of shrub communities in the Arctic.

4) A subsequent reduction in shrub cover in the coastal fen since ~AD 2000 and recolonization by mosses may be related to an increase in destructive grazing by Arctic snow geese. This may affect long-term carbon accumulation rates.

5) Our results show clear, albeit complex ecological responses to warming in these Arctic wetlands. These complexities have important implications for understanding of the future carbon sink potential of these ecosystems under climate warming and are important areas for future research.

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