Dear Prof. Alberto Reyes,

Please find uploaded the revised version of our manuscript, cp-2018-60, “Evidence for fire in the Pliocene Arctic in response to amplified temperature” for resubmission to *Climate of the Past*.

After discussion we have decided that the we are at an impasse with regard to the utility and application of the BRYOCARB and novel empirical model. As a result, we have removed the CO₂ analysis from the revised manuscript while maintaining discussion of our results within the context of the broader CO₂ record for the Pliocene.

Other changes to the manuscript in response to reviewers are detailed below, including clarifying and increasing the explicit discussion of feedbacks in the discussion in response to Dana Royer's suggestions.

We thank the reviewers and yourself for the time invested in this manuscript, and I hope the changes make this manuscript suitable for publication in *Climate of the Past*.

Sincerely,

Tamara Fletcher (On behalf of the authorship team)
Referee #1: Rienk Smittenberg

Although the paper is improved compared to the first submission, I still have major problems with their CO2 reconstruction. I would agree with their very general observation that higher pCO2 lead to greater isotope fractionation, however their empirical model has very high - but not well acknowledged - uncertainties rendering it not very useful for a quantitative paleoCO2 reconstruction.

Their basic isotope data are missing from the main text and their calculations are still not fully clear.

They introduce the Bryocarb model but do not give any details on it.

RE: We seem to be at an impasse due to differing opinions on the utility of BRYOCARB and the empirical model as devised for this study. As such, the CO2 component of this paper has been removed.

The general writing style is still not very good in part, and not built up logically here and there, this should be given a careful look (again).

I have uploaded an annotated pdf with more detailed comments.

Comments copied out of the PDF:

Line 138: Strike out (Δ 13 C)
RE: The CO2 component of this paper has been removed.

Line 141: Farquhar proposed to use Big delta 13C as a term for isotope fractionation effect (or discrimination) and this is still common in the ecosystem isotope literature. However there is a broader consensus of using epsilon for this, reserving Big Delta to express simply the difference between two pools/species. The isotope fractionation factor, again, is expressed by alpha. At the moment the various styles are mixed in the text and this is confusing. The authors need to be consistent in their isotope language.
RE: The CO2 component of this paper has been removed.

Line 144: Strike out isotopic fractionation
RE: The CO2 component of this paper has been removed.

Line 145 strike out –
RE: The CO2 component of this paper has been removed.

Line 147: Strike out in
RE: The CO2 component of this paper has been removed.

Line 157: What would be the effect of lowering pO2 levels, reducing the inhibition of photosynthesis due to photorespiration?

RE: The CO2 component of this paper has been removed.

Line 176: Note there is a 0.2 permil difference between growing season summer CO2 and mean mean annual.
RE: The CO2 component of this paper has been removed.

Line 178: explain what 'sub-fossil' entails here.
RE: The CO₂ component of this paper has been removed.

Line 179: reference to BRYOCARB model missing, and it is totally unclear what this model does and why it is used.
RE: The CO₂ component of this paper has been removed.

Line 181: At this point in the text it is fairly unclear what this transfer function entails, one would expect some equation.
RE: The CO₂ component of this paper has been removed.

Line 182: If the Bryocarb model is calibrated with own data then how can it be independent from that?
RE: The CO₂ component of this paper has been removed.

Line 185: sentence is oddly constructed and hard to understand, and I doubt you went back in time to the Pliocene
RE: The CO₂ component of this paper has been removed.

Line 186: simultaneous with what
RE: The CO₂ component of this paper has been removed.

Line 188: Strike out Δ₁³C and material
RE: The CO₂ component of this paper has been removed.

Line 189: There is a quite a large spread in isotope discrimination among different Tunda types, from 14 to 20 permil, with a very high sensitivity to mean annual temperature, see the figure from Buchman&Kaplan (2001) in Pataki et al (2003) GlobBiogeochemCycles17-1022
RE: The CO₂ component of this paper has been removed.

Line 189: if it is sensitive to altitude, does that not undermine the assumptions used to make the transfer function?
RE: The CO₂ component of this paper has been removed.

Line 192: why not take the ERA interim data?
RE: The CO₂ component of this paper has been removed.

Line 192: I assume one gets one (average) estimate of p(i)/p(a) because we only have one atm. 13C?
RE: The CO₂ component of this paper has been removed.

Line 206: MAAT?
RE: The suggested change has been made.

Line 221: Strike out The.
RE: The wording here has been changed.

Line 227: Strike out then.
RE: Change made
Calculating MST comes out of the blue in the text, needs to be introduced a little earlier
RE: This has been introduced at the end of section 2.3

It would be useful to mention the RMSE's of these calibrations, i.e. the uncertainty of the proxy (let alone the uncertainty in the measurements)
RE: This is now provided in equations 3, 4 and 5.

There are three stippled lines in Fig 3 one being the Bryocarb relation, this is confusing.
RE: The CO$_2$ component of this paper has been removed.

In my opinion this large spread of sensitivity is highly problematic. On top, they come from hugely different ecosystems with undoubtedly different types of mosses. Essentially the authors have (re)produced four estimates of the sensitivity (S) of fractionation with elevation, and it clearly shows that the various factors like humidity, temperature, but also possibly canopy effect, wind, etc, play into the game. In my opinion it is not warranted to pool all these results and come with one S, instead they should combine the four estimates of S which then has an uncertainty associated with it (also including the uncertainties of the individual S). That said, they come with a prediction interval in Fig. 3 that does have a spread of 7 permil for any given pCO2. In other words, one needs a 7 permil difference in 13C between fossil mosses arrive at the statement they grew under significantly different pCO2 levels.
RE: The CO$_2$ component of this paper has been removed.

But we are discussing the modern calibration here?
RE: The CO$_2$ component of this paper has been removed.

An estimate of the error of the slope (and intercept) is missing
RE: The CO$_2$ component of this paper has been removed.

13C x DELTA 13Cmoss ?
RE: The CO$_2$ component of this paper has been removed.

add table
RE: The CO$_2$ component of this paper has been removed.

and measured fossil moss 13C values. These values should be shown in the paper!!
RE: The CO$_2$ component of this paper has been removed.

Not clear at all where this 50ppm error comes from. It is different than the range of 296 - 480?
RE: The CO$_2$ component of this paper has been removed.

what is the transfer error?
RE: The CO$_2$ component of this paper has been removed.

That it is not different already shows from figure 3 where the Bryocarb solution falls within the 'empirical' range. The latter model is thus equally imprecise. Another problem
is the calibration range, which goes to 36 Pa (approx 360ppm) thus anything beyond that is an extrapolation - however there is no indication why the relation should be linear.
RE: The CO₂ component of this paper has been removed.

Lines 336-341: Anyone not intricately familiar with the brGDGT literature will be totally confused by these long sentences.
RE: Edits have been made to improve clarity.

Line 360: I'd say the quantification becomes different, not the abundance itself.
RE: This change has been made.

Line 376: If the RMSE of that calibration is +/- 2.5', how can a reconstruction be more precise?
RE: This is the standard deviation, not the RMSE. The text has been edited to reflect this.

Line 450: what is a 'slope of less isotopic discrimination'?
RE: The CO₂ component of this paper has been removed.

Line 460: and slopes
RE: The CO₂ component of this paper has been removed.

Line 469: The above is a good discussion. Concluding there are uncertainties in the approach. The next step is to quantify that uncertainty.
RE: The CO₂ component of this paper has been removed.

Line 475: Strike out highly variable
RE: The CO₂ component of this paper has been removed.

Line 480: 0.17 mg/C means??
RE: The CO₂ component of this paper has been removed.

Line 482: which one is that? the one of -20.9 permil?
RE: The CO₂ component of this paper has been removed.

Line 483: Abrupt transition about some other proxies,
RE: The CO₂ component of this paper has been removed.

Line 493: And then suddenly back to own estimates
RE: The CO₂ component of this paper has been removed.

Line 449: But that is only really because the ocean carbonate system cannot keep up at the moment exchanging and buffering the light C from fossil fuels. To sustain a very low 13CO₂ over a long time scale the geological C cycle needs to look very different. Is there any carbonate 13C evidence for low 13CO₂?
RE: The CO₂ component of this paper has been removed.

Line 555: Many grammatical errors in this paragraph
RE: The authors have made changes that we hope improve this paragraph

Line 582: Posited by whom?
RE: Change made. We posit that.

Line 602: where do these numbers come from?
RE: The exploratory CRACLE analysis described from 597. We now specify which analysis at that point in the text.

Line 649: Importantly, this is just one site and may not be representative for the entire Pliocene Arctic.
RE: Changes to this section of the text now highlight this point and the need for additional palaeofire studies at other sites in the CAA.

Line 654: add uncertainty
RE: This change has been made.

Referee #2: Dana Royer,

I’ll start my review with two core concerns:

1) There is a fundamental disconnect in the manuscript. The Abstract and Introduction set up as a central tenet the link between fire frequency and climate amplification in the Arctic:

Abstract: “One intriguing, but not fully understood, feature of the early to mid-Pliocene climate is the amplified arctic temperature response. Current models underestimate the degree of warming in the Pliocene Arctic and validation of proposed feedbacks is limited by scarce terrestrial records of climate and environment, as well as discrepancies in current CO2 proxy reconstructions. Here we reconstruct the CO2, summer temperature and fire regime from a sub-fossil fen-peat deposit”;

Introduction: “We propose that fire in arctic ecosystems may also be an important mechanism for amplifying arctic surface temperatures during the Pliocene, and so seek to understand its characteristics through quantification from the sediment record”.

But this theme is not returned to; not in the Abstract, and not in the Discussion. This leaves the reader unsatisfied. The authors do not even state whether temperature amplification exists for their site (beyond what is predicted from Pliocene global climate models), despite having the (summer) temperatures and CO2 concentrations to do so. That would be step 1.

Let’s assume that an exaggerated amplification is present (relative to GCMs). The authors have strong evidence for wildfire. Could wildfire amplify the temperature response to an increase in greenhouse gas forcing (relative to the feedbacks present in GCMs currently used for the Pliocene)? Again, the authors do not lay out these arguments.

An alternative approach would be to present the CO2, temperature, and fire data, and leave it at that, with only some minor comments about climate feedbacks. That is essentially how the manuscript is currently written, if one were to remove the above-mentioned sections in the Abstract and Introduction. That would be a fine paper.

RE: The authors consider that this theme was returned to in the discussion, both implicitly through discussion of the feedbacks between fire and temperature, fire and climate, vegetation and climate, and vegetation and fire, and explicitly 970–976 (current markup
manuscript line numbers). This section references the preliminary work conducted on wildfire as a feedback due to its “complex direct impacts on the surface radiative budget and direct and indirect effects on the top of the atmosphere radiative budget (Feng et al., 2016).”

The conclusion linked the interactions between climate, CO2, vegetation and fire. It also explicitly states the need for modelling experiments to “quantitatively investigate the effects [on climate] of the kind of fire regime presented here”.

To make the link to feedbacks clearer, have now changed the title of the manuscript, the discussion subheading, added short sections within the discussion that highlight the nature of these relationships as feedbacks, and added more details of the kinds of direct impacts we might expect in the final paragraph of the discussion. We have also devised a new figure that demonstrates the feedbacks between fire, vegetation and temperature in this ecosystem. This aspect has also been de-emphasised in the introduction through the removal of some background material.

2) Given the first set of reviews, I’m surprised that the authors continue to emphasize their empirical CO2 model. The fact that the BRYOCARB slope is shallower than the empirical one (Figure 3) should concern them. As the authors mention in the main text, there’s something funky going on with the Poland data. Those data steepen the empirical slope. As the authors also mention in the main text, the Andes data, which span the most elevation and perhaps have the least variability in other environmental factors (like moisture), show a shallower slope that looks close to the BRYOCARB slope. So why emphasize the empirical equation?? Especially because it requires extrapolation beyond the calibration data (which the authors do not acknowledge).

The errors with BRYOCARB are larger (= worse precision) because BRYOCARB more fully takes into account the various possible confounding factors. But the BRYOCARB estimates should be more reliable than the empirical ones (= more accurate), especially when applied to fossil settings, because they are underpinned by universal principles, not a series of regional, present-day empirical measurements.

Whether CO2 was 400 ppm or 500 ppm doesn’t make much of a difference for the authors’ story. The conceptual background of the BRYOCARB model, and the decisions for the inputs used in the model, need to be stated, though.

RE: As above, we seem to be at an impasse due to differing opinions on the utility of BRYOCARB and the empirical model as devised for this study. As such, the CO2 component of this paper has been removed.

More detailed comments:

Lines 24, 25: Need to say what the uncertainties represent (one-sigma, 95% confidence, etc.).
RE: The CO2 results have been removed and the information for temperature results has now been added.

Line 25: The reader won’t know what the “theoretical model” is. Some context is needed. Also, is 410 ppm “slightly lower” than 510 ppm (~20% difference)?
RE: The CO2 results have been removed and the information for temperature results has now been added.

Line 331: The uncertainty with the BRYOCARB CO2 estimate should be asymmetric. Have you computed it correctly?
RE: The CO2 component of this paper has been removed.

Lines 483-492: This paragraph doesn’t seem necessary. There’s no need to criticize other methods here.
RE: The CO2 component of this paper has been removed.

Lines 486-487: The residence time shouldn’t matter (other than needing to constrain the boron isotopic composition of sea water). What matters is the relative proportion of the two stable boron isotopes that is incorporated into carbonate minerals.
RE: The CO2 component of this paper has been removed.

Lines 498: What is the value based on forams?
RE: The CO2 component of this paper has been removed.

Line 616: “excepted”?
RE: This correction was made.

Line 654: Don’t give new information in the Conclusion (Eureka present-day summer temperature).
RE: This information is now introduced earlier in the discussion.

Figure 4: This would be easier to interpret if it were rotated 90 degrees clockwise, so that the vertical axis is age.
RE: This change, along with the deletion of the CO2 estimates, has been made.
Evidence for fire in the Pliocene Arctic in response to amplified temperature

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Abstract. The mid-Pliocene is a valuable time interval for investigating equilibrium climate at current atmospheric CO\textsubscript{2} concentrations, because atmospheric CO\textsubscript{2} concentrations are thought to have been comparable to current day and yet the climate and distribution of ecosystems was quite different. One intriguing, but not fully understood, feature of the early to mid-Pliocene climate is the amplified arctic temperature response and its impact on arctic ecosystems. Current models underestimate the degree of warming in the Pliocene Arctic and validation of proposed feedbacks is limited by scarce terrestrial records of climate and environment. Here we reconstruct the summer temperature and fire regime from a sub-fossil fen-peat deposit on west-central Ellesmere Island, Canada, that has been chronologically constrained using radionuclide dating to 3.9 +1.5/-0.5 Ma.

The estimate for average mean summer temperature is 15.4±0.8°C using specific bacterial membrane lipids, i.e. branched glycerol dialkyl glycerol tetraethers. Macro-charcoal was present in all samples from this Pliocene section with notably higher charcoal concentration in the upper part of the sequence. This change in charcoal was synchronous with a change in vegetation that saw fire promoting Pinus and Picea increase in abundance. Palaeovegetation reconstructions are consistent with warm summer temperatures, relatively low summer precipitation and an incidence of fire comparable to fire adapted boreal forests of North America, or potentially central Siberia.

To our knowledge, this site provides the northern-most evidence of fire during the Pliocene. It suggests that ecosystem productivity was much greater, providing fuel for wildfires, and that the climate was conducive to the ignition of fire during this period. This study indicates that interactions between palaeovegetation and paleoclimate were mediated by fire in the High Arctic during the Pliocene, even though CO\textsubscript{2} concentrations were similar to modern.

1 Introduction

Current rates of warming in the Canadian Arctic are now roughly triple the rate of global warming (Bush and Lemmen, 2019). Since 1850, global land surface temperatures have increased by approximately 1.0°C, whereas circum-arctic
land surface temperatures have increased by 2-2.0°C (Jones and Moberg, 2003; Francis and Skiff, 2015). Such arctic amplification of Arctic temperatures has also occurred during other warm climate anomalies in Earth’s past. Paleoclimate records from the Arctic indicate that the change in Arctic summer temperatures during past global warm periods was 3-4 times larger than global temperature change (Miller et al., 2010). While the latest ensemble of earth system models (ESMs) provide fairly accurate predictions of the modern amplification of arctic temperatures hitherto observed (Marshall et al., 2014), they often under-predict the amplification of arctic temperatures during past warm intervals in Earth’s history, including the Eocene (33.9-56 Ma; Shellito et al., 2009), and the Pliocene (2.6-5.3 Ma; Dowsett et al., 2012; Salzmann et al., 2013) epochs. These differences suggest that either the models are not simulating the full array of feedback mechanisms properly for past climates, or that the full array of fast and slow feedback mechanisms have not manifested for the modern Arctic. If the later, the Arctic region and its ecosystems have yet to reach a new equilibrium in response to full temperature amplification.

The Pliocene is an intriguing climatic interval that may offer important insights into climate feedbacks. Atmospheric CO₂ concentrations were, at times, as high as modern (Fig. 1), but generally show a decreasing trend throughout the Pliocene (Haywood et al., 2016; Pagani et al., 2010; Royer et al., 2007; Stap et al., 2016). Although CO₂ estimates from different methods do not converge, the modelled direct effects of these CO₂ discrepancies appear to be small (Feng et al., 2017). Of additional importance for comparability to the modern climate system, continental configurations were similar to present (Dowsett et al., 2016). While global mean annual temperatures (MATs) during the Pliocene were only 3°C warmer than present day, arctic land surface MATs may have been as much as 15 to 22°C warmer (Ballantyne et al., 2010; Csank et al., 2011a; Csank et al., 2011b; Fletcher et al., 2017). Further, arctic sea surface temperatures may have been as much as 10 to 15°C warmer than modern (Robinson, 2009), and sea-levels were approximately 25m higher than present (Dowsett et al., 2016). As a result, the Arctic terrestrial environment was significantly different from today, with boreal ecosystems at much higher latitudes (Salzmann et al., 2008). These changes in vegetation due to climate, may have also provided further important feedbacks to arctic temperatures (e.g. Otto-Bliisner and Upchurch Jr, 1997).

To advance our understanding of arctic ecosystem response and feedback to temperature amplification during past warm intervals in Earth’s history this investigation targets an exceptionally well-preserved arctic sedimentary sequence to simultaneously reconstruct summer temperature, vegetation and fire from a single site.

2 Methods

2.1 Site description

To investigate the environment and climate of the Pliocene Arctic we focused on the Beaver Pond (BP) fossil site, located at 78° 33’ N (Fig. 2) on Ellesmere Island. The stratigraphic section located at ~380 meters above sea level (MASL) today includes unconsolidated bedded sands and gravels, and rich organic layers including a fossil rich peat layer, up to 2.4 m thick, with sticks gnawed by an extinct beaver (Dipoides spp.). The assemblage of fossil plants and animals at BP has been studied extensively to gain insight into the past climate and ecology of the Canadian High Arctic (Ballantyne et al., 2006; Csank et al., 2011a; Csank et al., 2011b; Fletcher et al., 2017; Mitchell et al., 2016;...
Rybczynski et al., 2013; Tedford and Harington, 2003; Wang et al., 2017). Previous paleoenvironmental evidence suggests the main peat unit is a rich fen deposit with a neutral to alkaline pH, associated with open water (Mitchell et al., 2016), likely a lake edge fen or shallow lake fen, within a larch-dominated forest-tundra environment (Matthews and Fyles, 2000), not a low pH peat-bog. While the larch species identified at the site, *Larix groenlandia*, is extinct (Matthews and Fyles, 2000), many other plant remains are Pliocene examples of taxa that are extant (Fletcher et al., 2017).

The fen-peat unit examined in this study was sampled in 2006 and 2010. The main sequence examined across the methods used in this study includes material from Unit II, the entire span of Unit III, and material from Unit IV sampled from Section A as per Mitchell et al. (2016; Fig. S1; see Mitchell et al. 2016 Fig 5), with a total sampled profile of 1.65 m. Unit III has been estimated to represent ~20 000 years of deposition based on modern northern fen accumulation rates (Mitchell et al., 2016). The charcoal estimates from this locality were based on 31 sample layers from the 2006 field campaign, while the temperature estimates from specific bacterial membrane lipids were taken from 22 of the sample layers collected in 2006 and an additional 12 samples collected in 2010. The same samples from the 2006 season were analyzed for mean summer temperature and charcoal content where contents of the sample allowed. Pollen was tabulated from 10 samples from the 2006 sequence, located at different stratigraphic depths.

2.2 Geochronology

While direct dating of the peat was not possible, we were able to establish a burial age for fluvial sediments deposited approximately 4–5 m above and 30 m to the southwest of the peat. We used a method based on the ratio of isotopes produced in quartz by secondary cosmic rays. The cosmogenic nuclide burial dating approach measures the ratio of cosmogenic $^{26}$Al (t$_{1/2}$ = 0.71 Ma) and $^{10}$Be (t$_{1/2}$ = 1.38 Ma) in quartz sand grains that were exposed on hilltops and alluvium prior to final deposition at BP. Once the quartz grains are completely shielded from cosmic rays, the ratio of the pair will predictably decrease because $^{26}$Al has double the radiodecay rate of $^{10}$Be. In 2008, four of the medium to coarse grained quartz samples were collected from a vertical profile of planar crossbedded fluvial sands between 8.7 and 10.4 m below the overlying till surface. The samples were 5 cm thick, separated by an average of 62 cm, and should closely date the peat (the sandy braided stream beds represent on the order of ~10$^4$ years from the top of the peat to the highest sample). Quartz concentrates were extracted from the arkosic sediment using Frantz magnetic separation, heavy liquids, and differential leaching with HF in ultrasonic baths. When sample aliquots reached aluminum concentrations <100 ppm (ICP-OES) as a proxy of feldspar abundance, the quartz concentrate was subjected to a series of HF digestion and rinsing steps to ensure that more than 30% of the quartz had been dissolved to remove meteoric $^{10}$Be. Approximately 200 mg of Be extracted from a Homestake Gold Mine beryl-based carrier was added to 150 g of each quartz concentrate (no Al carrier was needed for these samples). Such large quartz masses were digested because of the uncertainty in the abundance of the faster decaying isotope. Following repeated perchloric-acid dry-downs to remove unreacted HF, pH-controlled precipitation, column chemistry ion chromatography to extract the Be and Al ions, precipitation in ultrapure ammonia gas, and calcination at temperatures above 1000°C in a Bunsen flame for three minutes, oxides were mixed with equal amounts of niobium and silver by volume. These were packed into stainless steel targets for measurement at Lawrence Livermore National Laboratory’s...
accelerator mass spectrometer (AMS). Uncertainty estimates for $^{26}$Al/$^{27}$Al were calculated as 1σ by combining AMS precision with geochemistry errors in quadrature. For a complete detailed description of TCN methods see Rybczynski et al. (2013). The ages provided here are updated from Rybczynski et al. (2013) by using more recent production rate information and considering the potential for increasing exposure to deeply penetrating muons during the natural post-burial exhumation at BP.

2.3 Paleotemperature Reconstruction

Paleotemperature estimates were determined based on the distribution of fossilized, sedimentary membrane lipids known as branched glycerol dialkyl glycerol tetraethers (brGDGTs) that are well preserved in peat bogs, soils, and lakes (Powers et al., 2004; Weijers et al., 2007c). These unique lipids are thought to be synthesized by a wide array of Acidobacteria within the soil (Sinninghe Damsté et al., 2011; Sinninghe Damsté et al., 2014) and presumably other bacteria (Sinninghe Damsté et al., 2018) in soils and peat bogs but also in aquatic systems. Previously, it has been established that the degree of methyl branching (expressed in the methylation index of branched tetraethers; MBT) is correlated with mean annual air temperature (MAAT), and the relative amount of cyclcopetanone moieties (expressed in the cyclization index of branched tetraethers; CBT) has been shown to correlate with both soil pH and MAAT (Weijers et al., 2007b). Because of the relationship of the distribution of these fossilized membrane lipids with these environmental parameters, it has been used for paleoclimate applications in different environments including coastal marine sediments (Bendle et al., 2010; Weijers et al., 2007a), peats (Ballantyne et al., 2010; Naafs et al., 2017), palcosols (Peterse et al., 2011; Zech et al., 2012), and lacustrine sediments (Loomis et al., 2012; Niemann et al., 2012; Pearson et al., 2011; Zink et al., 2010). In this study we reconstruct mean summer air temperature (MST), using a modified version of a calibration that was developed by Pearson et al. (2011) and is based on 90 core top lacustrine sediment samples from diverse climates and geographical areas.

Improved separation methods (Hopmans et al., 2016) have recently led to the separation and quantification of the 5- and 6-methyl brGDGT isomers that used to be treated as one since the 6-methyl isomers were co-eluting with the 5- methyl isomers (De Jonge et al., 2013). This has led to the definition of new indices and improved MAAT calibration based on the global soil (De Jonge et al., 2014), peat (Naafs et al., 2017), and African lake (Russell et al., 2018) datasets.

Sediment samples were freeze-dried and then ground and homogenized with a mortar and pestle. Next, using the Dionex™ accelerated solvent extractors (ASE), 0.5–1.0 g of sediment was extracted with the solvent mixture of dichloromethane (DCM):methanol (9:1, v/v) at a temperature of 100°C and a pressure of 1500 psi (5 min each) with 60% flush and purge 60 s. The Caliper Turboprep®LV was utilized to concentrate the collected extract, which was then transferred using DCM and dried over anhydrous Na$_2$SO$_4$ before being concentrated again under a gentle stream of N$_2$ gas. To quantify the amount of GDGTs, 1 µg of an internal standard (C46 GDGT; Huguet et al., 2006) was added to the total lipid extract. Then, the total lipid extract was separated into three fractions using hexane:DCM (9:1, v/v) for the apolar fraction, hexane:DCM (1:1, v/v) for the ketone fraction and DCM:MeOH (1:1, v/v) for the polar fraction, using a column composed of Al$_2$O$_3$, which was activated for 2 h at 150°C. The polar fraction, which contained the GDGTs, was dried under a steady stream of N$_2$ gas and weighed before being re-dissolved in hexane/isopropanol deleted.
(99:1, v:v) at a concentration of 10 mg mL\(^{-1}\) and subsequently passed through a 0.45 µm PTFE filter. Finally, the polar fractions were analyzed for GDGTs by ultra-high performance liquid chromatography – atmospheric pressure positive ion chemical ionization – mass spectrometry (UHPLC-APCI-MS) using the method described by Hopmans et al., (2016). The polar fractions of some samples were re-run on the UHPLC-APCI-MS multiple times and the average fractional abundances of the brGDGTs was determined.

For the calculation of brGDGT-based proxies, the brGDGTs are specified by the Roman numerals as indicated in Fig. S2. The 6-methyl brGDGTs are distinguished from the 5-methyl brGDGTs by a prime. The novel indices, including MBT′\(_{\text{MA}}\) based on just the 5-methyl brGDGTs and the CBT′ that was used to calculate the pH (De Jonge et al., 2014):

\[
\text{MBT}_{\text{MA}} = (\text{Ia} + \text{Ib} + \text{Ic}) \times (\text{Ia} + \text{Ib} + \text{Ic} + \text{IIa} + \text{IIb} + \text{IIc} + \text{IIIa} + \text{IIIb} + \text{IIIc}) (2) \\
\text{CBT′} = -19 \log ([\text{Ia}] + [\text{IIa′}] + [\text{IIb′}] + [\text{IIc′}] + [\text{IIIa′}] + [\text{IIIb′}] + [\text{IIIc′}]) / ([\text{Ia}] + [\text{IIa}] + [\text{IIIa}]) (2)
\]

The square brackets denote the fractional abundance of the brGDGT within the bracket relative to the total brGDGTs.

The distributions of aquatically produced brGDGTs in the lake calibration developed by Pearson et al. (2011) were used to determine MST. When this calibration is used the fractional abundances of Ila and Ila′ must be summed because these two isomers co-eluted under the chromatographic conditions used by Pearson et al. (2011):

\[
\text{MST (°C)} = 20.9 + 98.1 \times [\text{Ib}] - 12 \times ([\text{IIa}] + [\text{IIa′}]) - 20.5 \times [\text{IIIa}] \quad \text{RMSE} = 2.0 ^\circ \text{C} \quad (2)
\]

MA\(_{\text{AT}}\) and surface water pH were also calculated using a novel calibration created using sediments from East African lakes analysed with the novel chromatography method and based upon MBT\(_{\text{MA}}\) (Russell et al., 2018).

\[
\text{MA}_{\text{AT}} = -1.2141 + 32.4223 \times \text{MBT}_{\text{MA}} \quad \text{RMSE of 2.44 °C} \\
\text{Surface water pH} = 8.95 + 2.65 \times \text{CBT′} \quad \text{RMSE of 0.80} (2)
\]

### 2.4 Vegetation and Fire Reconstruction

For charcoal, a total of thirty 2 cm\(^2\) samples were taken at 5 cm intervals from depths from 3.89 to 3.45 MASL at the BP site, with an additional 2 cm\(^2\) sample collected at 3.15 MASL. All samples were deflocculated using sodium hexametaphosphate and passed through 500, 250 and 125 µm nested mesh sieves. The residual sample caught on each sieve was then collected in a gridded petri dish and examined using a stereomicroscope at 20-40X magnification to obtain charcoal concentration (fragments cm\(^{-2}\)). Charcoal area (mm\(^2\) cm\(^{-2}\)) was measured for each sample using specialized imaging software from Scion Corporation. For a detailed description of methods see Brown and Power (2013).

Vegetation was reconstructed using pollen and spores (herein pollen) at selected elevations chosen to capture upper and lower sections of the elevation profile, and that corresponded with changes in charcoal. The sample depths selected for pollen analyses were 3.10–3.35 MASL, 3.51–3.5 MASL, and 3.15–3.45 MASL. Samples were
processed using standard approaches (Moore et al., 1991), whereby 1cm³ sediment subsamples were treated with 5% KOH to remove humic acids and break up the samples. Carbonates were dissolved using 10% HCl, whereas silicates and organic was removed by HF and acetylation treatment, respectively. Pollen slides were made by homogenizing 35 µl of residue, measured using a single-channel pipette, with 15 µl of melted glycerin jelly. Slides were counted using a Leica DM4000 B LED compound microscope at 400–630x magnification. A reference collection and published keys (McAndrews et al., 1973; Moore et al., 1991) aided identification.

In addition to tabulating pollen and charcoal, a list of plant taxa derived from Beaver Pond was previously compiled in Fletcher et al. (2017). Extant species from this list were selected and their modern occurrences extracted from the Global Biodiversity Information Facility (GBIF.org, 2017). Observation data was grouped by 5º latitude 5º longitude grids cells, and the shared species count calculated using R (R Core Team, 2016). Modern fire frequency was mapped using the MODIS 6 Active Fire Product. The fine pixel detection count per day, within the same 5º latitude 5º longitude grids cells was counted over the ten years 2006–2015, and standardized by area of the cell. The modern climate maps were generated using data from WorldClim 1.4 (Hijmans et al., 2005). The values for the bioclimatic variables mean temperature of the warmest quarter (equivalent to °MST) and precipitation of the warmest quarter (summer precipitation) were also averaged by grid cell. The shared species count, climate values, and fire day detections were mapped to the northern polar stereographic projection in ArcMap 10.1.

3 Results

3.1 Geochronology

The burial dating results with 26Al/27Al in quartz sand at 10 m below modern depth provides four individual ages. From shallowest to deepest, the burial ages are 3.6 ± 0.3 Ma, 3.9 ± 0.4 Ma, 4.1 ± 0.6 Ma, and 4.0 ± 0.4 Ma (Table S2), with an unweighted mean age of 3.9 Ma. The convoluted probability distribution function yields a maximum probability age of 4.5 Ma. Unfortunately, the positive tails of the probability distribution functions of two of the samples exceeds the radiodecay saturation limit of the burial age. Therefore, their probability distributions do not reflect the actual age probabilities and uncertainty. Given the positive tail in the probability distribution functions, and the inability to convolve all samples, we recommend using the unweighted mean age, 3.9 Ma, with an uncertainty of ±1.5 ± 0.5 Ma as indicated by the two samples with unsaturated limits. Despite the apparent upward younging of the individual burial ages, the 1σ-uncertainties overlap rendering the samples indistinguishable.

3.2 Paleotemperature Estimates

3.2.1 Provenance of branched GDGTs

Previously, brGDGT derived MAAT estimates (-0.6 ± 5.0 °C) from BP sediments were developed using the older chromatography methods that did not separate the 5- and 6- methyl brGDGTs, and a soil calibration (Ballantyne et al., 2010). In marine and lacustrine sediments, bacterial brGDGTs were thought to originate predominantly from continental soil erosion arriving in the sediments through terrestrial runoff. More recent studies, however, have indicated aquatically produced brGDGTs could be affecting the distribution of the sedimentary brGDGTs and thus...

 Deleted: mean summer air temperature; 
 Deleted: Atmospheric C CO2 Reconstruction

As expected, carbon isotopic discrimination in mosses shows a positive relationship with partial pressure of atmospheric CO₂, both in empirical observations and theoretical predictions (Fig. 3). However, a much greater change in δ¹³C moss is observed in measurements than predicted from ERA-interim BRYOCARB simulations. The empirical fit to the observed change in δ¹³C moss is better than the theoretical prediction from the BRYOCARB model (RMSE = 2.1 ‰, but the slopes are quite different, with our empirical slope (0.6 ± 5.0 °C) from BP sediments was developed using the older model of Braconnot et al., 2008). While the two models fit the data, we recommend using the empirical model in the future when developing δ¹³C moss in the field.

The burial dating results with 26Al/27Al in quartz sand at 10 m below modern depth provides four individual ages. From shallowest to deepest, the burial ages are 3.6 ± 0.3 Ma, 3.9 ± 0.4 Ma, 4.1 ± 0.6 Ma, and 4.0 ± 0.4 Ma (Table S2), with an unweighted mean age of 3.9 Ma. The convoluted probability distribution function yields a maximum probability age of 4.5 Ma. Unfortunately, the positive tails of the probability distribution functions of two of the samples exceeds the radiodecay saturation limit of the burial age. Therefore, their probability distributions do not reflect the actual age probabilities and uncertainty. Given the positive tail in the probability distribution functions, and the inability to convolve all samples, we recommend using the unweighted mean age, 3.9 Ma, with an uncertainty of ±1.5 ± 0.5 Ma as indicated by the two samples with unsaturated limits. Despite the apparent upward younging of the individual burial ages, the 1σ-uncertainties overlap rendering the samples indistinguishable.

Based on our analysis of cellulose extracted from four different Myriophyllum sp. (i.e. buckbean) plants growing at four different locations in the modern boreal forest, we found δ¹³C moss to be fairly constant 10 ± 0.4‰, yielding an estimate of δ¹³C moss in modern buckbean of 0.5. Applying this modern δ¹³C moss to our δ¹³C measurements from sub-fossil buckbean we obtained estimates of δ¹³C moss during the Pliocene of -6.23 ± 0.9 ‰. Using our empirical transfer function (Eq. 9) in combination with these estimates of δ¹³C moss, we were able to approximate atmospheric CO₂ concentrations over the Pliocene interval captured at the BP site (Fig. 4). We estimated a mean atmospheric CO₂...
the temperature estimates based upon them (Warden et al., 2016; Zell et al., 2013; Zhu et al., 2011). Since the discovery that sedimentary brGDGTs can have varying sources, different calibrations have been developed depending on the origin of the brGDGTs, i.e. soil calibration (De Jonge et al., 2014), peat calibration (Naafs et al., 2017) and aquatic calibrations (i.e. Foster et al., 2016; Pearson et al., 2011; Russell et al., 2018). Therefore, several studies have recommended that the potential sources of the sedimentary brGDGTs should be investigated before attempting to use brGDGTs for paleoclimate applications (De Jonge et al., 2015; Warden et al., 2016; Yang et al., 2013; Zell et al., 2013). In this study, we examine the distribution of brGDGTs in an attempt to determine their origin and consequently choose the most appropriate calibration to utilize in order to reconstruct temperatures from the BP sediments.

Branched GDGTs IIIa and IIIa′ on average had the highest fractional abundance of the brGDGTs detected in the BP sediments (see Fig. S2 for structures; Table S4). A previous study established that when plotted in a ternary diagram the fractional abundances of the tetra-, penta- and hexamethylated brGDGTs, soils lie within a distinct area (Sinninghe Damsté, 2016). To assess whether the brGDGTs in the BP deposit were predominantly derived from soils, we compared the fractional abundances of the tetra-, penta- and hexamethylated brGDGTs in the BP sediments to those from modern datasets in a ternary diagram (Fig. 3). Since the contribution of brGDGTs from either peat or aquatic production could affect the use of brGDGTs for paleoclimate application, in addition to comparing the samples to the global soil dataset (De Jonge et al., 2014), peat and lacustrine sediment samples were added into the ternary plot to help elucidate the provenance of brGDGTs in the BP sediments. According to Sinninghe Damsté (2016), it is imperative to only compare samples in a ternary diagram like this where all of the datasets were analyzed with the novel methods that separate the 5- and 6-methyl brGDGTs since the improved separation can result in an increased quantification of hexamethylated brGDGTs. Recently, samples from East African lake sediments were analyzed using these new methods (Russell et al., 2018) and so these samples were included in the ternary plot for comparison (Fig. 3). Although the lakes from the East African dataset are all from a tropical area, they vary widely in altitude and, thus, in MAAT. We separated them into three categories by MAAT (lakes >20°C, lakes between 10-20°C and lakes<10°C). By comparing all the samples in the ternary plot, it was evident that the BP samples plotted closest to the lacustrine sediment samples from regions in East Africa with a MAAT <10°C, suggesting that the provenance of the majority of the brGDGTs from the BP sediments was not soil or peat but lacustrine aquatic production.

The average estimated surface water pH for the BP sediments (8.6±0.2) calculated using eq. (5) is within the 6–9 range typical of lakes and rivers (Mattson, 1999). This value is near the upper limit of rich fens characterized by the presence of S. scorpioides (Kooijman and Westhoff, 1995; Kooijman and Paulissen, 2006) and is higher than what would be expected for peat-bog sediments that are acidic (pH 3–6; Clymo, 1964) and which constitute most of the peats studied by Naafs et al. (2017). A predominant origin from lake aquatic production is in keeping with previous interpretation of the paleoenvironment of the BP site, which was at least at times covered by water as evidenced by fresh water diatoms, fish remains and gnawed beaver sticks in the sediment (Mitchell et al., 2016).

### 3.2.2 Aquatic Temperature Transfer Function

Since there is evidence that the majority of the brGDGTs in the BP sediments are aquatically produced, an aquatic transfer function was used for reconstructing temperature. When we apply the African lake calibration (Eq. 4),
resulting estimated MAAT for BP is 7.1 ± 1.0 °C (mean ± standard deviation). This value is high compared to other
previously published estimates from varying proxies, which have estimated MAAT in this region to be in the range
of -5.5 to 0.8 °C, (Ballantyne et al., 2010; Ballantyne et al., 2006; Csank et al., 2011a; Csank et al., 2011b; Fletcher et
al., 2017). A concern when applying this calibration is that it is based on lakes from an equatorial region that does not
experience substantial seasonality, whereas, the Pliocene Arctic BP site did experience substantial seasonality
(Fletcher et al., 2017). Biological production (including brGDGT production) in BP was likely skewed towards
summer and, therefore, summer temperature has a larger influence on the reconstructed MAAT. Unfortunately, no
global lake calibration set using individually quantified 5- and 6-methyl brGDGTs is yet available. Therefore, to
calculate MST (Eq. 3) we applied the aquatic transfer function developed by Pearson et al. (2011) by combining the
individual fractional abundances of the 5- and 6-methyl brGDGTs. The Pearson et al. (2011) calibration was based on
a global suite of lake sediments including samples from the Arctic, thus covering a greater range of seasonal
variability. The resulting average estimated MST was 15.4 ± 0.8 °C (average ± standard deviation), with temperatures
ranging between 14.1 and 17.4 °C (Fig. 4). This is in good agreement with recent estimates based on Climate
Reconstruction Analysis using Coexistence Likelihood Estimation (CRACLE; Fletcher et al., 2017) that concluded
that MSTs at BP during the Pliocene were approximately 13 to 15°C.

3.3 Vegetation and Fire Reconstruction

All sediment samples from BP contained charcoal (Fig. 4), indicating the consistent prevalence of biomass burning in
the High Arctic during this time period. However, counts were variable throughout the section, with the middle and
lower sections (mean 34 fragments cm⁻³) containing less charcoal compared to the upper section upper section (mean
444 fragments cm⁻³). Overall, samples from BP contained on average 100.0 ± 165 fragments cm⁻³ (mean ± 1 σ), with
charcoal area averaging 12.3 ± 20.2 mm² cm⁻³. The variability of charcoal within any given sample was relatively low
with a 1 σ among charcoal area of approximately 2 mm² cm⁻³.

The three parts of the section analysed for pollen (3.0-3.3, 3.3-3.4 MASL, 3.3-3.4 MASL, and 3.3-3.4 MASL) reveal variations in vegetation (Figs. 4 and 5). Near the bottom of the section (3.0-3.3, 3.4 MASL), Larix
(26%) and Betula (17%) were the dominant trees. Alnus (6%) and Salix (6%) together with ericaceous pollen (4%) were relatively high. In contrast, low numbers of Picea (3%), Pinus (3%) and fern spores were recorded. Additional
wetland taxa like Myrica (5%) and Cyperaceae (6%) were also noted. Overall, the non-arboreal (23%) signal was well
developed. Crumpled and/or ruptured inaperturate grains with surface sculpturing that varied from scabrate to
verricate were noted in the assemblage (12%), but could not be definitely identified. It is possible that these grains
represent Populus, Cupressaceae or additional Cyperaceae pollen. Between 3.3-3.4 MASL, Larix (38%) and
Betula (21%) increased in abundance, followed by ferns (7%). Cyperaceae remained at similar levels (6%) whereas
Picea and Pinus decreased to 2% and 1%, respectively. Unidentified inaperturate types collectively averaged 14%.

Larix pollen (23%) remained abundant near the top of the section (3.3-3.4 MASL), whereas Betula (2%) decreased. Picea (16%) Pinus (6%) and ferns (23%) increased in abundance. Of the ferns, trilete spores and cf.
Botrychium were most abundant, followed by cf. Dryopteris. Inaperturate unknowns (10%) were also observed. Other
notables included Ericaceae (2%) and Cyperaceae (2%). While rare, Onagraceae grains were also observed (Fig. 5).
According to the GBIF-based mapping exercise, the paleofloral assemblage at BP most closely resembles modern vegetation found in northern North America, particularly on the eastern margin (e.g. New Hampshire, New Brunswick and Nova Scotia) and the western margin (Alaska, Washington, British Columbia, and Alberta; Fig. 7a), and central Fennoscandia. Of these areas, the western coast of northern North America and eastern coast of southern Sweden has the most similarity to the reconstructed BP climate in terms of MST (Fig. 7b) and summer precipitation (Fig. 7c).

While high counts of active fire days are common in the western part of the North American boreal forest, it is not as common in the eastern part of the North American boreal forest (Fig. 7d), likely due to the differences in the precipitation regime. There were also low fire counts in Fennoscandia likely due to historical severe fire suppression (Brown and Giesecke, 2014; Niklasson and Granström, 2004). Therefore, based on our reconstruction of the climate and ecology of the BP site, our results suggest that BP most closely resembled a boreal-type forest ecosystem shaped by fire, similar to those of Washington, British Columbia, Northwest Territories, Yukon and Alaska (but see Sect. 4.3).

4 DISCUSSION

4.1 Geochronology

The plant and animal fossil assemblages observed at BP suggest a depositional age between 3 and 5 Ma (Matthews Jr and Ovenden, 1990; Tedford and Harington, 2003). This biostratigraphic age was corroborated with an amino-acid racemization age (2.4 ± 0.5 Ma) and Sr-correlation age (2.8–5.1 Ma) on shells (Brigham-Grette and Carter, 1992) in biostratigraphically correlated sediments on Meighen Island, situated 375 km to the west-north-west. The previously calculated burial age of 3.4 Ma for the BP site is a minimum age because no post-depositional production of 26Al or 10Be by muons was assumed. If the samples are considered to have been buried at only the current depth (ca. 10 m, see supplemental data) then the ages plot to the left and outside of the burial field, indicating that the burial depth was significantly deeper for most of the post-depositional history. The revised cosmogenic nuclide burial age is 3.9 ± 1.5/0.5 Ma. It is the best interpretation of burial age data based on improved production rate systematics (e.g. Lifton et al., 2014), and more reasonable estimates of erosion rate and ice cover since the mid-Pliocene (see Fig. S3, Table S5).

As the stratigraphic position of the cosmogenic samples is very close to the BP peat layers, we interpret the age to represent the approximate time that the peat was deposited.

4.2 Fire, vegetation, temperature: a feedback triangle

Wildfire is a key driver of ecological processes in modern boreal forests (Flannigan et al., 2009; Ryan, 2002), and although historically rare, is becoming more frequent in the tundra in recent years (Mack et al., 2011). The modern increase in fire frequency is likely as a consequence of atmospheric CO2 driven climate warming and feedbacks such as reduced sea ice extent (Hu et al., 2010), because the probability of fire is highest where temperature and moisture are conducive to growth and drying of fuels followed by conditions that favor ignition (Whitman et al., 2015). Young et al. (2017) confirmed the importance of summer warmth and moisture availability patterns in predicting fire across Alaska, highlighting a July temperature of ~13.5 °C as a key threshold for fire across Alaska.
The abundance of charcoal at BP demonstrates that climatic conditions were conducive to ignition and that sufficient biomass available for combustion existed across the landscape. brGDGTs-derived temperature estimates suggest mean summer temperatures at BP exceeded the −13.5 °C threshold (Young et al., 2017) that drastically increases the chance of wildfire. Indeed, the estimate of −15.4°C suggests summer temperatures is −11°C higher than modern day Eureka, Canada (−4.1°C, Fig. 2). Given a global mean increase of 3°C for the Pliocene compared to modern (see fig. 1) this 11°C increase represents 3.6x arctic amplification of temperature (NB. although comparing summer temperatures to mean global temperature increase is likely imprecise, given much increase of arctic warmth in Pliocene climate models is from winter warming (see Ballantyne at al. 2013) 3.6x is likely an underestimate rather than an overestimate.) Without increasing arctic amplification of temperature that accompanies increasing CO₂, mean summer temperatures would fall below the −13.5°C threshold. This is evidence that Pliocene arctic amplification of temperatures was a direct feedback to increased wildfire activity, but also an indirect feedback as the increased extent of boreal forest into the higher latitudes, also possible due to arctic amplification of temperatures, provided the fuel (Fig. 6)

An increase in atmospheric convection has been simulated in response to diminished sea-ice during warmer intervals (Abbot and Tziperman, 2008), but this study did not confirm if this increase in atmospheric convection was sufficient to cause lightning ignitions. An alternative ignition source for combustion of biomass on Ellesmere Island during the Pliocene is coal seam fires, which have been documented to be burning at this time (Estrada et al., 2009). However, given the interaction of summer warmth and ignition by lightning within the same climate range as posited for BP, we consider lightning the most likely source of ignition for Pliocene fires in the High Arctic.

Fire return intervals cannot be calculated from the BP charcoal counts due to the absence of a satisfactory age-depth model and discontinuous sampling. As strong interactions are observed between fire regime and ecosystem assemblage in the boreal forest (Brown and Giesecke, 2014; Kasischke and Turetsky, 2006), and in response to climate, comparison with modern fire regimes for areas with shared species compositions and climates may inform a potential range of mean fire return interval (MFRI).

Matthews and Fyles (2000) indicated that the Pliocene BP environment was characterized by an open larch dominated forest-tundra environment, sharing most species in common with those now found in three regions, including central Alaska to Washington in western North America, the region centered around the Canadian/US border in eastern North America, as well as Fennoscandia in Europe. The modern area with the most species in common with BP is central northern Alaska (Fig. 7A). The area over which shared species were calculated is largely tundra, but includes the ecotone between tundra and boreal forest. Other zones that share many species with BP are continuous with Alaska down the western coast of North America to the region around the border of Canada and the United States, the eastern coast of North America in the region around the border of Canada and the United States (~50°N), and central Fennoscandia. Of these zones, the MST of Alaskan tundra sites (6–9°C) are less similar to BP (15.4°C) than ~50°N on both western and eastern coastal North American sites and central Fennoscandia (12–18°C, Fig. 7B). The eastern coast of North America has higher rainfall during the summer (>270 mm), than the west coast and Alaska (Fig. 7C), which correlates to the timing of western fires. The low summer precipitation for much of the west (<200 mm), is consistent with previously published summer precipitation estimates for BP (~190 mm). As a result, the fire regime of the west coast ~50°N may be a better analogue for BP than the east coast of North America. In central
Fennoscandia there is also a west vs. east coastal variation in summer precipitation with the western, Nordic part of the region experiencing higher summer precipitation (252–288 mm), than the more similar eastern, Swedish part of the region (~198 mm).

Investigation of the modern fire detection data (Fig. 7D) suggests that the two regions most climatically similar to BP, ~50°N western North America and central Sweden, have radically different fire regimes. It is likely this is caused by historical fire suppression in Sweden that limits the utility of modern data for comparison with this study (Brown and Giesecke, 2014; Niklasson and Granström, 2004). To understand the fire regimes, as shaped by climate and species composition rather than human impacts, we considered both the modern and recent Holocene reconstructions for these regions (Table 1). This shows that, a) within any region variation arises from the complex spatial patterning of fire across landscapes, and b) that the regions most similar to BP (~50°N western North American and eastern Fennoscandian reconstructions for the recent Holocene) have shorter fire return intervals than the cooler Alaskan tundra or wetter summer ~50°N region of the eastern North American coast.

While the shared species for Siberia appears low, the number of observations in the modern biodiversity database used is likewise low – perhaps causatively so. Given the similar climate to BP on the Central Siberian Plateau and some key aspects of the floras in Siberia such as the dominance of larch, we considered the fire regime of the larch forests of Siberia. Khanuk et al. (2016; 2011) studied MFRIs across Siberia, from 64°N to 71°N, the northern limit of larch stands. They found an average MFRI across that range of 110 years, with MFRI increasing from 80 years in the southern latitudes to ~300 in the north (Table 1). Based on similarity of the climate variables, the more southerly MFRIs (~80 years) may be a better analogue. Key differences between boreal fires in North America compared to Russia are a higher fire frequency with more burned area in Russia, but a much lower crown fire and a difference in timing of disturbance, with spring fires prevailing in Russia compared to mid-summer fires in western Canada (de Groot et al., 2013; Rogers et al., 2015).

The pollen-based vegetation reconstruction derived in this study indicates that open Larix-Betula parkland persisted in the basal (380.3–350.4 MASL) parts of the sequence. Groundcover was additionally dominated by shrub birch, ericaceous heath and ferns. While the regional climate may have been somewhat dry, the record suggests that, locally, a moist fen environment dominated by Cyperaceae, existed near the sampling location. Shrubs including Alnus and Salix likely occupied the wetland margins.

The corresponding relatively low concentration of charcoal may reflect lower severity fires or higher sedimentation rates. We consider the former more likely due to the depositional environment of Unit III from Mitchell et al. 2016, a lake edge fen peat in a beaver pond or small lake, without evidence of high sediment influx overwhelming peat production. We posit that a surface fire regime, somewhat like that in southern central Siberia existed. This premise is also supported by the fire ecology characteristics of the dominant vegetation. Larix does not support crown fires due to leaf moisture content (de Groot et al., 2013) and self-pruning (Kobayashi et al., 2007). The persistence and success of larch in modern-day Siberia appears to be driven by its high growth rate (Jacquelyn et al., 2017) tolerance of frequent surface fire due to thick lower bark (Kobayashi et al., 2007) and tolerance of spring drought due to its deciduous habit (Berg and Chapin III, 1994). Arboreal Betula are very intolerant of fire and easily girdled. However, they are quick to resprout and are often found in areas with short fire return intervals. Like Larix, arboreal Betula have
high moisture content of their foliage and are not prone to crown fires. Betula nana L., an extant dwarf birch, is a fire
endurer that resprouts from underground rhizomes or roots (Racine et al., 1987) thus regenerating quickly following
lower severity fires (de Groot et al., 1997). The vegetation and fire regime characteristics are similar further up the
sequence at 3.10-3.15 MASL, with the exception that fens increased in abundance while heath decreased.

In the upper part of the sequence (3.35-3.45 MASL), where charcoal was abundant, the Larix-Betula parkland
was replaced by a mixed boreal forest assemblage with a fen understory. Canopy cover was more closed compared
to the preceding intervals. The forest was dominated by Larix and Picea, with lesser amounts of Pinus. While Betula
remained part of the forest, it decreased in abundance possibly due to increased competition with the conifers. Based
on exploratory CRACLE analyses of climate preferences using GBIF occurrence data (GBIF.org, 2018a, b, c, d) of
the dominant taxa (Larix-Betula vs. Larix-Picea-Pinus), the expansion of conifers could indicate slightly warmer
summers (MST ~15.8 °C vs. 17.1 °C). This result differs from the stable MST estimated by bacterial tetraethers,
although within reported error, and the small change is certainly within the climate distributions of both communities.

The CRACLE analyses also suggest that slightly drier conditions may have prevailed during the three wettest months
(249-285mm vs. 192-219mm). While the interaction between climate, vegetation and fire is complex, small changes
in MST and precipitation could have directly altered both the vegetation and fire regime, which in turn further
promoted fire adapted taxa. In addition to regional climatic factors, community change at the site may have been
further influenced by local hydrological conditions, such as channel migration, pond infilling and ecosystem
engineering by beaver (Cantar spp.).

The high charcoal content of the upper portion (~ Unit IV) of the sequence has three potential explanations:
reworking of previously deposited charcoal, decreased sedimentation, or increased wildfire production of charcoal.
We consider the first unlikely because there is no difference in the shape of the macrocharcoal between the upper and
lower portions of the sequence, whereas we would anticipate a change in the dimensions of the charcoal if it had
undergone additional physical breakdown from reworking (see Fig. 5c). The second, decreased sedimentation, may
occur if the deposition is a result of infrequent, episodic flooding intermixed with long periods during which charcoal
was deposited. The recorded sedimentology does not support this explanation, but due to the complexity of flooding
processes, also does not disprove this explanation. We, however, favour the third explanation of increased wildfire
due to the change in plant composition consistent with a greater influence of fire. If accepted, it is likely that frequent,
mixed severity fires persisted. While Larix is associated with surface fire, Picea and Pinus are adapted to higher
intensity crown fires. A crown fire regime may have established as conifers expanded, altering fuel loads and
flammability. For example, black spruce sheds highly flammable needles, its lower branches can act as fuel ladders
facilitating crown fires (Kasischke et al., 2008), and it was previously tentatively identified at BP (Fletcher et al.,
2017). While it has thin bark and shallow roots maladapted to survive fire (Auclair, 1985; Brown, 2008; Kasischke et
al., 2008), it releases large numbers of seeds from semi-serotinous cones, leading to rapid re-establishment (Côté et
al., 2003). The documentation of Onagraceae pollen at the top of the sequence could potentially reflect post-fire
succession. For example, the species Epilobium angustifolium L. is an early-seral colonizer of disturbed (i.e. burned)
sites, pollinated by insects.
It appears that the *Larix Betula* parkland dominated intervals correspond to the peat- and sand-stratigraphic Units II and III described by Mitchell et al. (2016), whereas the mixed boreal forest in the upper part of the sequence is contemporaneous with Unit IV, described as peat and peaty sand, coarsening upwards. While it is clear that the vegetation and fire regimes changed through time at this Arctic site, temperatures appear more stable, or at least to have no apparent trend. Thus, it is suggested that the fire regime at BP was primarily regulated by regional climate and vegetation, and perhaps additionally by changing local hydrological conditions. Regarding climate, MST remained high enough (~13.5°C) throughout the sequence to allow for fire disturbance and the pollen suggests that temperatures may have marginally increased in the upper part of the sequence. Alternatively, other climate variables, such as the precipitation regime, or local hydrological change may have initiated the change in community. Up-sequence changes in vegetation undoubtedly influenced fine fuel loads and flammability. Indeed, the fire ecological characteristics of the vegetation are consistent with a regional surface fire regime yielding to a crown fire regime.

*Betula and Alnus*, which occurred earlier in the depositional sequence, are favored by beaver in foraging (Bush, 1996; Haarberg and Rosell, 2006; Jenkins, 1979). Moreover, the presence of sticks cut by beaver in Unit III reveals that beavers were indeed at the site, moistening the local land surface. The lack of beaver cut sticks and changes in sediment in Unit IV may indicate that the beavers abandoned the site, possibly in response to changes in vegetation (i.e. increased conifers and decreased *Betula*) limiting preferred forage or due to lateral channel migration, as evidenced by the coarsening upward sequence described by Mitchell et al. (2016). As a result, the local land surface may have become somewhat drier, contemporaneous with the change towards *Larix-Picea-Pinus* forest and a mixed severity fire regime.

Critically, the charcoal record at BP suggests substantial biomass burning that could have acted as a feedback mechanism amplifying or dampening warming during the Pliocene. Its potential role as a feedback to climate is suggested by its prevalence through time, and forest fire's complex direct impacts on the surface radiative budget (e.g. black carbon deposition on snow and ice) and direct and indirect effects on the top of the atmosphere radiative budget (i.e. aerosol emissions, Feng et al., 2016). Further investigation through both investigation of the fire record at other Arctic sites and modelling experiments using varying fire regimes and extent is warranted to better characterize the fire regime in order to improve accuracy of fire simulations in earth system models of Pliocene climate.

5. CONCLUSION

The novel temperature estimates presented here confirm that summer temperatures were considerably warmer during the Pliocene (15.4 ± 0.8°C) compared to the modern Arctic. The ~11°C higher summer temperatures at Beaver Pond support an increasing influence of arctic amplification of temperatures when CO₂ reaches and exceeds modern levels. Our reconstruction of the paleovegetation and ecology of this unique site on Ellesmere Island suggests an assemblage similar to forests of the western margins of North America and eastern Fennoscandia. The evidence of recurrent fire and concurrent changes in taxonomic composition are indicators that fire played an active role as a feedback in Pliocene Arctic forests, shaping the environment as it does in the boreal forest today. Evidence from fire in the modern boreal forest suggests that fire may have had direct and indirect impacts on Earth’s radiative budget at high latitudes during the Pliocene, acting as a feedback to Pliocene climate. The net impact of the component process remains
unknown and modelling experiments are needed to quantitatively investigate the effects of the kind of fire regime presented here, on the Pliocene High Arctic. Collectively, these reconstructions provide new insights into the palaeoclimatology and palaeoecology of the Canadian High Arctic, ~3.9 Ma.

Data Availability. The data generated and used in this analysis are available in the supplemental information associated with this article.

Sample Availability. Samples used in this analysis are curated by the Canadian Museum of Nature. Sample numbers used for each analysis are given in the supplemental information (Table S3 and S4).

Supplemental Link. To be provided by Copernicus Publishing


Competing interests. The authors declare that they have no conflict of interest

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References


de Lafontaine, G. and Payette, S.: Shifting zonal patterns of the southern boreal forest in eastern Canada associated with changing fire regime during the Holocene, Quaternary Science Reviews, 30, 867–875, 2011.


Table 1. Modern and recent Holocene fire return interval reconstructions for the candidate analogous regions considered in this study.

<table>
<thead>
<tr>
<th>Region</th>
<th>Modern</th>
<th>Reference</th>
<th>Recent Holocene</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alaskan Tundra</td>
<td>Seward Peninsula</td>
<td>Kasischke et al. (2002)</td>
<td>Up-Valley</td>
<td>Higuera et al. (2011)</td>
</tr>
<tr>
<td></td>
<td>Nulato Hills</td>
<td>273*</td>
<td>Down-valley</td>
<td>142</td>
</tr>
<tr>
<td></td>
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<td></td>
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<tr>
<td>Alaskan Boreal</td>
<td>Porcupine/</td>
<td>Johnstone et al. (1981)</td>
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<tr>
<td></td>
<td>Upper Yukon</td>
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<tr>
<td></td>
<td>(Central)</td>
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<td></td>
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<td></td>
<td>Sites near</td>
<td>Johnstone et al. (2010a);</td>
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<tr>
<td></td>
<td>Fairbanks, and</td>
<td>Johnstone et al. (2010b);</td>
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<tr>
<td></td>
<td>Delta Junction</td>
<td>Johnstone and Kasischke (2005)</td>
<td></td>
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<tr>
<td></td>
<td>(Central)</td>
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<tr>
<td>Yukon river</td>
<td></td>
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<td>Brooks Range</td>
<td></td>
</tr>
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<td></td>
<td>145</td>
<td>Higuera et al. (2009)</td>
</tr>
<tr>
<td>Kuskokwim</td>
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<td></td>
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<tr>
<td>Mountains</td>
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<tr>
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<td>and Valleys</td>
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<td>~69</td>
<td>Greene and Daniels (2017)</td>
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<td>~500*</td>
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<td>418*</td>
<td>Bergeron et al. (2006 post-1940)*</td>
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<tr>
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<td>Quebec – Abitibi southwest</td>
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* denotes post-1940 data.
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<tr>
<th>Location</th>
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<th>Location</th>
<th>14C Age (yr)</th>
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<td>Quebec – Temiscamingue south</td>
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<tr>
<td>Quebec – Waswanipi</td>
<td>418*</td>
<td>Quebec – Central Quebec</td>
<td>128</td>
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<td>Quebec – Central Quebec</td>
<td>388*</td>
<td>Quebec – Central Quebec</td>
<td>150</td>
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<tr>
<td>Quebec – North Shore</td>
<td>645*</td>
<td>Quebec – North Shore</td>
<td>281</td>
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<td>Quebec – Gaspésia</td>
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<tr>
<td>Quebec – northwestern – lakeshore</td>
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<td>63'</td>
</tr>
<tr>
<td>Quebec – northwestern – lake island</td>
<td>112'</td>
<td>Quebec – northwestern – lake island</td>
<td>74'</td>
</tr>
</tbody>
</table>

**Fennoscandia**

- **Sweden**
  - **North Sweden**: 50-150
  - **Southern Sweden**: 20
- **Central Sweden**: *: Brown and Giesecke (2014)
  - **Central Sweden - Klotjärnen**: 180
  - **Central Sweden - Holtjärnen**: 240

**Siberian Plateau**

- **Northern**: 300
- **Southern**: 80
- **Mean (64°-71°N)**: 110

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* = The reciprocal converted from burn rate (%) (see Van Wagner et al., 2006)

* = Estimates likely effected in some areas by human activity. In such instances Recent Holocene is preferred.

† = 'Recent' here refers to records that (or have distinct sections that) begin after the end of the Holocene Climate Optima and end near present.
Figure 1: Global temperatures and atmospheric CO$_2$ concentration spanning the last 5 million years of Earth’s history. Mean annual temperatures (MAT) are inferred from compiled $\delta^{18}$O foraminifera data (Lisiecki and Raymo, 2005) and plotted as anomalies from present (top panel). Modern atmospheric CO$_2$ measurements (NOAA/ESRL), and ice core observations from EPICA (Luthi et al., 2008) are compared with proxy estimates (bottom panel; see Table S1) for the Pliocene Epoch indicated with beige shading. Smoothed curves have been fit to highlight trends in $p$CO$_2$ and temperature during the Pliocene.
Figure 2. Map of the Canadian Arctic Archipelago, highlighting the location of the Beaver Pond Site (Black Star; 78° 33′ N; 82° 25′ W) and Eureka Climate Station (Grey Star; 80° 13′ N, 86° 11′ W – used for modern climate comparison) on west-central Ellesmere Island.
Figure 3. A ternary plot illustrating the fractional abundances of the tetramethylated (Ia-c), pentamethylated (IIa-c and II′a-c), and hexamethylated (IIIa-c and III′a-c) brGDGTs. The global soil dataset (open circles; De Jonge et al., 2014), the global peat samples (green circles; Naafs et al., 2017), and lake sediments from East Africa (black circles) indicate samples from lakes >20°C, red circles indicate samples from lakes between 10–20°C and orange circles designate samples from lakes <10°C; Russell et al., 2018) are included for comparison with the Beaver Pond sediments (blue circles; this study).

Figure 3. Sensitivity of carbon isotopic discrimination to the partial pressure of atmospheric CO₂ in mosses sampled from different elevational transects. Moss carbon isotope data collected from an elevational transects in the Swiss Alps (black dots; Ménot and Burns, 2001), the Peruvian Andes (blue dots; Royles et al., 2014), the mountains of Poland (red dots; Skrzypek et al. 2007), and Hawaii (green dots; Waite and Sack 2011). Partial pressure of atmospheric CO₂ calculated from atmospheric surface pressure reanalysis data (Dee et al., 2011) combined with atmospheric CO₂ observations from year moss samples were collected. All carbon isotopic measurements of mosses have been normalized to cellulose based on published regression of cellulose and whole moss values (Ménot and Burns, 2001) and reported as discrimination (Δ) from atmospheric δ¹³CO₂ (Global View-CO₂, 2013) from the year mosses were collected in units of ‰. Empirical model fit (black line) is plotted with prediction intervals (black dashed) compared with predictions from the BRYOCARB model (blue dashed; Fletcher et al. 2008) with parameters optimized to match observations.
Figure 4. Reconstruction of mean summer temperature and fire for the Canadian High Arctic during the Pliocene. Mean summer air temperature reconstructed from a brGDGT based proxy (blue; ± 2σ) and relative 2010 data point in approximate relative position (purple; ± 2σ). Charcoal counts reported as the number of fragments per volume (fragments cm⁻³) of peat (Orange ± 2σ). Green boxes indicate relative depths of pollen sampling. Elevation of the deposit is reported as meters above sea level. (Data: Table S3)
Figure 5. (A) Bar charts showing the relative pollen abundance in each portion of the section (error bars = 95% confidence intervals; MASL - Meters Above Sea Level). (B). Pollen plate of select grains encountered in the BP section: (a) *Pinus*, (b) half a *Picea* grain, (c) *Larix*, (d) *Betula*, (e) *Alnus*, (f) *Salix*, (g) *Myrica*, (h) ericaceous grain, (i) *Epilobium*, and (j) Cyperaceae. 50um scale = (a–c), 75um scale = (d–j).
Figure 6: Examples of the feedbacks between temperature, vegetation and wildfire at the Beaver Pond site.
Figure 7. (a) Modern geographic distribution of observed occurrences of species common to the Beaver Pond species list, (b) Mean temperature of the warmest quarter (summer average) derived from WorldClim, (c) Mean precipitation of the warmest quarter (summer rain) derived from WorldClim, (d) Count of unique fire pixels detected per day, over 10 years from MODIS 6 Fire Product, normalized by area of the latitude by longitude grid.