Paper:

Hiemstra, J. (2018). Permafrost and environmental dynamics: A virtual issue of The Holocene. *The Holocene, 28*(8), 1201-1204.
http://dx.doi.org/10.1177/0959683618785835

EDITORIAL

Permafrost and environmental dynamics: a virtual issue of *The Holocene*

'Today is grey skies, tomorrow is tears...' (Waits, 1987)

With surface temperatures changing at a rate that is roughly twice the global average (IPCC, 2013), the Arctic region is currently experiencing significant environmental change. Higher surface temperatures and longer growing seasons are causing a northward shift of the boreal forest. The growth of shrubs and woody vegetation at the expense of sedges, grasses and mosses, an effect that has been described as the 'greening' of the Arctic, can be traced back at least to the early 1980s (Sturm *et al*., 2001; Epstein *et al*., 2012; Xu *et al*., 2013; Ju and Masek, 2016).

Increasing temperatures also lead to the degradation of permafrost. At present, permafrost covers around a quarter of the Northern Hemisphere land surface (Ballantyne, 2018), but this area is shrinking fast. In northern Russia for example, the southern limits of both discontinuous and continuous permafrost have moved northwards by between 50 and 80 km in the past decades (IPCC, 2013). Such migrations of permafrost boundaries have been observed across the whole of the Arctic region and there is no indication that such shifts will come to a halt any time soon (e.g. Lawrence *et al*., 2012). Associated with the thawing permafrost are the widespread occurrence of thermokarst and the development of ponds and lakes, bringing with it significant changes in the region's hydrology (van Huissteden *et al*., 2011; Karlsson *et al*., 2014).

One aspect of degrading permafrost that has rightfully received a lot of attention is the decomposition of currently frozen organic matter in Arctic soils - estimated to hold around half of the underground carbon reserves - and the anticipated release of large quantities of carbon dioxide and methane into the atmosphere. The exact quantities of future emissions are still uncertain, which is the reason why the carbon feedback from permafrost thaw was not included in the climate modelling reported by the IPCC (2013), but there is a strong consensus that this carbon source will become increasingly prominent over the next few decades (Schuur *et al*., 2013; 2015).

The uncertainties in the prediction of future Arctic carbon budgets are due in large part to the roles that hydrology and vegetation play in permafrost dynamics (e.g. Zhuang *et al*., 2006; Burke *et al*., 2012). Permafrost dynamics are intricately linked with changes in ground surface conditions brought about by thermokarst, localised waterlogging or desiccation, which provide different feedbacks on further permafrost changes, both positive and negative. Carbon emissions are known to be significantly higher under aerobic than under anaerobic conditions (ACIA, 2005), whilst thermokarst ponds, often supersaturated with greenhouse gases, have been shown to emit very high levels of methane (Walter *et al*., 2006). Interestingly, emission of carbon dioxide from such water bodies is often less than expected, which may be explained by an increase of photosynthetic activity resulting from the colonisation by aquatic macrophytes and growth of benthic microbial mats (Breton *et al*., 2009). Similarly, the encroachment of sedges on pond edges may lead to the initiation of hydrosere succession (Sturm *et al*., 2001) and a reduction of pond size over time (Andresen and Lougheed, 2015), both of which have the ability to offset carbon emissions.

The perhaps unexpected role of changing vegetation in relation to thermokarst development was also demonstrated in a study by Briggs *et al*. (2014), who showed that, rather than water bodies accelerating permafrost degradation underneath, permafrost actually re-formed in response to shrub (*Salix*) encroachment around the edges of lakes. They argued that the shrubs locally provide shading, and change infiltration characteristics and heat transport in the soil and thus promote permafrost aggregation, albeit temporary.

Even the aforementioned greening of the Arctic is not as clear-cut and intuitive as it may seem. First, in the context of carbon emissions, the increase of vegetation biomass and photosynthetic activity that occur above ground are evident, but the processes of respiration and decomposition below ground still throw up interesting questions about the region's future as a potential carbon source (e.g. Davidson and Janssens, 2006). Second, there is an important regional variability in the greening: the trend is unambiguous in the North Slope region of Alaska, the tundra regions of southern Canada and central and eastern Siberia, but less so in western Alaska, western Siberia and the Canadian High Arctic (Richter-Menge *et al.*, 2016). In fact, Epstein *et al.* (2015) observed a significant reversal i.e. a 'browning' trend from 2011 to 2014, mainly in the Eurasian Arctic. There has been some speculation about the causes, but whether this browning represents a blip or a new trajectory is a valid and relevant question and underscores the uncertainties that exist in this area of modern permafrost science (Phoenix and Bjerke, 2016).

'…you'll have to wait 'til yesterday is here.' (Waits, 1987)

From the review above it will have become clear that the modern Arctic is a highly dynamic environment and that it harbours complex interrelationships between hydrology, permafrost and vegetation, both from both a temporal and a spatial perspective. The highlighted 'modern' studies also seem to suggest that the complexity is governed to a large extent by the region's heterogeneity and that significant changes can unfold over very short timescales.

This 'volatility' of the permafrost environment and the obvious gaps in our knowledge of present-day processes makes a strong case for applying uniformitarian principles. In this respect, the Holocene provides an excellent 'temporal' laboratory. The Holocene period is recent enough to provide reliable data and long enough to have confidence in patterns or trends that may be shown by these data. The Holocene is also characterised by a climate that was relatively stable in the long term but shows significant variability on shorter timescales. Anomalies such as the Holocene Climatic Optimum, the Medieval Warm Period and the Little Ice Age are all of magnitudes that provide very good analogues for current and near-future Arctic climate scenarios.

This provides the backdrop and the rationale for the present *Permafrost and Environmental Dynamics* virtual issue. The objective is to bring together papers from the back catalogue of *The Holocene* that look into aspects of vegetation and/or hydrological change in relation to climate-induced permafrost dynamics. The nine papers, summarised below in no particular order, describe studies carried out in locations from across the Arctic and sub-Arctic region (**Figure 1**). It is envisaged that this virtual issue will be used in conjunction with an older special issue of *The Holocene* (Yu *et al.*, 2014) to provide a springboard for future studies in the highly relevant research area of permafrost dynamics.

<FIGURE HERE?>

Figure 1. – Study sites covered in the selected studies. For numbers refer to the main text.

The Holocene laboratory: nine selected papers

Arlen-Pouliot and Bhiry (2005) investigated the close interrelationship between climate, vegetation and permafrost along the eastern coast of Hudson Bay (**Figure 1 – location 1**). At present, the study site can be characterised as a sedge fen located in the sporadic permafrost zone. The area comprises several palsas, some still with a core of ground ice, and some 'collapsed' into thermokarst ponds. In this study, peat cores were taken from an intact palsa and a filled-in thermokarst pond with the objective to investigate the area's permafrost dynamics, and to evaluate the influence of a suite of potential autogenic (e.g. climate) and allogenic factors (e.g. peat accumulation rates). Based on core stratigraphy and macrofossil content it was found that peat began to accumulate shortly after 6,000 yr BP in a salty marsh environment, and that since that time different freshwater biomes have prevailed. Starting as a rich fen (5,640 – 4,610 yr BP), the area changed to a poor fen from 4,200 yr BP until 1,760 yr BP. Between then and the Little Ice Age, ombrotrophication changed the area to a bog largely due to an increased rate of peat accumulation. Permafrost is thought to have established firmly during the Little Ice Age, leading to the development of palsas. More recently, in response to climate warming and increased precipitation, the palsas have begun to disappear again. This started the development of a landscape of thermokarst ponds and vegetation dominated by mosses such as *Calliergon* and *Sphagnum*.

Arlen-Pouliot and Bhiry's study shows many parallels to the study by **Oksanen *et al.*** (2001), except that the latter was carried out in the European Russian Arctic (**Figure 1 – location 2**) on a dry peat plateau. This site is currently located in the discontinuous permafrost zone. Macrofossils in peat records indicate that the oldest *Betula* trees date back to c. 9,500 yr BP whilst conifers, such as *Picea*, date back to c. 8,000 yr BP. Oksanen *et al*. found that tree stands became rare in the area after c. 2,800 yr BP and suggest that the present-day peatlands formed through terrestrialization of ponds and/or the paludification of forested uplands. Between 9,000 and 3,100 yr BP the peatlands are thought to have been wet rich fens, but since that time, marked periods of cooling (*c.* 3,100 yr BP; *c*. 2,200 yr BP; *c.* 600 yr BP) instigated the aggradation of permafrost and brought about considerable change to the area's surface hydrology, in turn leading to dominance of Sphagnum species in the regional vegetation.

Blyakharchuk and Sulerzhitsky (1999) studied pollen and macrofossil records from an elevated palsa bog in western Siberia (**Figure 1 – location 3**) to reconstruct climatic and environmental change through the Holocene. At present, the study site is situated in the boreal forest and underlain by discontinuous permafrost. The core records indicate that at the start of the Holocene the region experienced a dry, cold climate, in which permafrost was widespread and probably continuous. Later, at around 9,700 – 9,500 yr BP, the tundra-steppe vegetation, dominated by Betula, got gradually replaced by tundra dominated by *Larix* and *Picea*, which suggests a change to a warmer and wetter climate, and the development of thermokarst and a northward shift of the continuous permafrost limit. Later still, an abundance of *Abies* was used to infer that the wettest and warmest period in the region occurred between 6,500 – 5,500 yr BP. The present-day vegetation, represented by *Pinus* and *Sphagnum* communities, is thought to have started to develop c. 5,500 yr ago when a cooling instigated a southward shift of the (discontinuous) permafrost and a coincident southward retreat of *Abies* forests. Arguably the most marked change from wet-mire peat to woody peat at c. 1 m below the palsa surface, and dated to c. 4,300 yr BP, signifies a further cooling, the slowing down of peat accumulation and the kick-starting of the ground-ice formation that developed into the palsa landform.

The Holocene peat accumulation in the continuous permafrost region of (Sub-)Arctic Canada (**Figure 1 – locations 4a and 4b**) was the subject of a study by **Vardy *et al. (2000)***. Specifically it aimed to provide an estimate of past rates of carbon storage in peatlands in the Northwest Territories and Nunavut. Both areas today show tundra-wetland vegetation with a ground cover of *Carex* and *Sphagnum* and a variety of dwarf shrubs, such as *Betula* and *Empetrum*. The peat cores were found to show a considerable variation in carbon accumulation rates over the course of the Holocene with mean values that are significantly lower than those found for other boreal peatlands. It is proposed that this may be associated with other studies not considering the possibility of high ground ice contents. The carbon accumulation rates were found to be particularly low for the last 3,500 - 4,500 years in the higher latitudes, whilst one of the cores from the lower latitudes showed particularly high rates for the last 800 years. Some of the highest accumulation rates were found in units representing fen stages or transitional periods from fen to bog peat. In the higher latitudes, such units were found to have formed between 4,000 and 8,000 yr BP, whilst in the Subarctic this phase seems to have occurred significantly earlier: 10,100 - 9,500 yr BP.

Sannel and Kuhry (2008) studied Holocene vegetation succession and permafrost dynamics on two peat plateaus in west-central Canada (**Figure 1 – location 5**). At present, one of the sites is in the continuous permafrost zone - within the ecotone between boreal forest and tundra - while the other site lies in an open *Picea* forest in the discontinuous permafrost zone. Macrofossil analysis and radiocarbon dating of the peat profiles showed that peat inception took place around 5,800–5,100 yr BP and was associated with a short-lived phase of permafrost degradation. It was also found that permafrost was already present at the northernmost site at that time, and that permafrost conditions have been remarkably stable. At both sites there is evidence of permafrost thaw which facilitated the colonisation by wet fen species such as *Carex* and *Sphagnum*, but subsequent permafrost aggradation is thought to have occurred with the establishment of *Sphagnum fuscum* at c. 4,000 yr BP and c. 4,900 yr BP for the northern and southern site respectively. Old radiocarbon dates from the upper parts of the cores (2,800 – 1,100 yr BP) corroborate the previously reported dates for cessation of peat growth in the region. Reasons put forward to explain the apparent drier surface conditions include improved local drainage, cooler climate and elevation due to frost heave processes.

Pelletier *et al.* (2017) report on a study of Holocene permafrost dynamics, palaeoecology and carbon storage in Scotty Creek, NW Territories, Canada (**Figure 1 – location 6**). At present the site is located in the discontinuous permafrost zone. The landscape comprises, in order of dominance, permafrost peat plateaus, thermokarst bogs, channel fens and lakes, with a vegetation of open canopy *Picea* and *Larix* and a ground cover of Sphagnum. Three peat cores were investigated and it was found that limnic and minerotrophic peat accumulation was dominant before permafrost formed around 5,000 yr BP. Three distinct periods of permafrost aggradation were identified in a core recovered from a peat plateau profile, while permafrost was only found to have aggraded once in a thermokarst bog core. The period from 1,250 yr BP to present was inferred to be the coldest and wettest since the Holocene Thermal Maximum and permafrost aggradation in this period was observed in all cores. Climate is acknowledged as an allogenic driver but it is also pointed out that permafrost aggradation may not have occurred if the peat had been thinner and less isolated from the groundwater. The roles of autogenic controls are thus highlighted as complicating factors in predictions of future carbon budgets in permafrost regions.

The allogenic and autogenic controls on permafrost dynamics were also the theme of the study by **Ouzilleau Samson *et al.*** (2010), who investigated a core from Nunavik, Quebec, Canada (**Figure 1 – location 7**). The site is presently a peatland underlain by continuous permafrost, and is characterised by a tundra vegetation of grass, moss and *Carex* with shrubs of *Betula* and *Salix*. The stratigraphic record suggests shrub tundra vegetation between 2,340 and 1,910 yr BP, with an active layer that was relatively shallow. Between 1,910 and 1,100 yr BP, the abundance of *Sphagnum* suggests a period of warmer and more humid conditions and a deepening of the active layer. Subsequent colder and drier conditions starting around 1,100 yr BP are indicated by rootlet and sedge peat facies, and an increase in aeolian sedimentation. A short return to *Sphagnum* and thus warmer and humid conditions occurred between 870 – 670 yr BP. The brevity of this period led the authors to propose that no significant degradation of permafrost would have taken place at the time. The period between 670 yr BP and the present (including the Little Ice Age) was inferred to be colder, windier and drier again with Sphagnum losing out to an herbaceous tundra vegetation.

Ulrich *et al.* (2017) focused on permafrost degradation in Central Yakutia, Russia (**Figure 1 – location 8**) around the Holocene Climatic Optimum. At present, the study site is grassland alas with isolated pingos set within a taiga biome characterised by *Larix* and *Pinus*. From within one of the pingos a 900-year core was recovered. The first stage of thermokarst was inferred to have occurred between c. 6,750 and 6,500 yr BP, with terrestrial conditions quickly changing to lacustrine conditions. A lake was reconstructed to rapidly emerge and grow to an estimated size of up to 600 m diameter and 15 m depth in only 150 years between c. 6,500 and 6,350 yr BP. Thermokarst processes were found to cease completely after 5,870 yr BP, when the lake disappeared and talik refroze, most likely due to climatic changes. At this time, the growth of the present-day pingo was initiated. The study emphasises that short-term warming led to very active permafrost degradation and rapid but locally variable modification of alas and thermokarst evolution.

Wolter *et al.* (2017) studied a short core recovered from the Yukon Coastal Plain in northwest Canada (**Figure 1 – location 9**). Today the area lies in the continuous permafrost zone and can be characterised as a tundra wetland with grasses, mosses, and dwarf shrubs. The core was found to span the past three centuries and based on variations in grain-size, pollen, and C/N ratios, it was established that relatively cool conditions prevailed before AD 1850. Since that time, at the end of the Little Ice Age, the area experienced a gradual warming of the climate. Interestingly, little variation in abundance of regional pollen was noted between AD 1730 and AD 2012 indicating that the regional vegetation was not particularly sensitive, i.e. resilient to the climate warming. This was attributed to species migration and competition being important drivers of vegetation dynamics. The record does show a response to climate warming in the region in the form of an apparent deepening of the lake from AD 1910 which is taken as evidence of localised permafrost thaw subsidence.

References

ACIA (2005) Arctic Climate Impact Assessment. Cambridge: Cambridge University Press, 1042 pp.

Andresen CG and Lougheed VL (2015) Disappearing Arctic tundra ponds: Fine-scale analysis of surface hydrology in drained thaw lake basins over a 65 year period (1948–2013). *Journal of Geophysical Research: Biogeosciences* 120: 466–479.

Arlen-Pouliot Y and Bhiry N (2005) Palaeoecology of a palsa and a filled thermokarst pond in a permafrost peatland, subarctic Québec, Canada. *The Holocene* 15: 408-419.

Ballantyne CK (2018) Periglacial Geomorphology. Chichester: Wiley-Blackwell, 454 pp.

Blyakharchuk TA and Sulerzhitsky LD (1999) Holocene vegetational and climatic changes in the forest zone of Western Siberia according to pollen records from the extrazonal palsa bog Bugristoye. *The Holocene* 9: 621-628.

Breton J, Vallières C and Lauriona I (2009) Limnological properties of permafrost thaw ponds in northeastern Canada. *Canadian Journal of Fisheries and Aquatic Sciences* 66: 1635-1648.

Briggs MA, Walvoord MA, McKenzie JM, *et al*. (2014) New permafrost is forming around shrinking Arctic lakes, but will it last? *Geophysical Research Letters* 41: 1585-1592.

Burke EJ, Hartley IP and Jones CD (2012) Uncertainties in the global temperature change caused by carbon release from permafrost thawing. *The Cryosphere* 6: 1063-1076.

Davidson EA and Janssens IA (2006) Temperature sensitivity of soil carbon decomposition and feedbacks to climate change. *Nature* 440: 165-173.

Epstein HE, Raynolds MK, Walker DA, *et al*. (2012) Dynamics of aboveground phytomass of the circumpolar Arctic tundra during the past three decades. *Environmental Research Letters* 7: 015506.

Epstein HE, Bhatt US, Raynolds MK, *et al*. (2015) Tundra greenness. *In*: Jeffries MO, Richter-Menge J and Overland JE (eds) Arctic Report Card: update for 2015. NOAA: Silver Spring, MD.

IPCC (2013) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Stocker TF, Qin D, Plattner G.-K., et al. (eds) Cambridge: Cambridge University Press, 1535 pp.

Ju J and Masek JG (2016) The vegetation greenness trend in Canada and US Alaska from 1984–2012 Landsat data. *Remote Sensing of the Environment* 176: 1–16.

Karlsson JM, Lyon SW and Destouni G (2014) Temporal behavior of lake size-distribution in a thawing permafrost landscape in northwestern Siberia. *Remote Sensing* 6: 621-636.

Lawrence D, Slater A and Swenson S (2012) Simulation of present-day and future permafrost and seasonally frozen ground conditions in CCSM4. *Journal of Climatology* 25: 2207-2225.

Oksanen PO, Kuhry P and Alekseeva RN (2001) Holocene development of the Rogovaya River peat plateau, European Russian Arctic. *The Holocene* 11: 25-40.

Ouzilleau Samson D, Bhiry N and Lavoie M (2010) Late-Holocene palaeoecology of a polygonal peatland on the south shore of Hudson Strait, northern Québec, Canada. *The Holocene* 20: 525-536.

Pelletier N, Talbot J, Olefeldt D, Turetsky M, Blodau C, Sonnentag O and Quinton WL (2017) Influence of Holocene permafrost aggradation and thaw on the paleoecology and carbon storage of a peatland complex in northwestern Canada. *The Holocene* 27: 1391-1405.

Phoenix GK and Bjerke JW (2016) Arctic browning: extreme events and trends reversing arctic greening. *Global Change Biology* 22: 2960-2962.

Richter-Menge J, Overland JE and Mathis JT (eds) (2016) Arctic Report Card 2016, www.arctic.noaa.gov.

Sannel ABK and Kuhry P (2008) Long-term stability of permafrost in subarctic peat plateaus, west-central Canada. *The Holocene* 18: 589-601.

Schuur EAG, Abbott BW, Bowden WB, *et al*. (2013) Expert assessment of vulnerability of permafrost carbon to climate change. *Climate Change* 119: 359-374.

Schuur EAG, McGuire AD, Schädel C, *et al*. (2015) Climate Change and the permafrost carbon feedback. *Nature* 520: 171-179.

Sturm M, Racine C and Tape K (2001) Climate change: Increasing shrub abundance in the Arctic. *Nature* 411: 546-547.

Ulrich M, Wetterich S, Rudaya N, *et al*. (2017) Rapid thermokarst evolution during the mid-Holocene in Central Yakutia, Russia. *The Holocene* 27: 1899-1913.

van Huissteden J, Berrittella C, Parmentier FJW, *et al*. (2011) Methane emissions from permafrost thaw lakes limited by lake drainage. *Nature Climate Change* 1: 119–123.

Vardy SR, Warner BG, Turunen J, *et al*. (2000) Carbon accumulation in permafrost peatlands in the Northwest Territories and Nunavut, Canada. *The Holocene* 10: 273-280.

Waits T (1987) Yesterday is here. *In*: Franks Wild Years [CD]. Universal Recording.

Walter KM, Zimov SA, Chanton JP, *et al*. (2006) Methane bubbling from Siberian thaw lakes as a positive feedback to climate warming. *Nature* 443: 71-75.

Wolter J, Lantuit H, Herzschuh U, *et al*. (2017) Tundra vegetation stability versus lake-basin variability on the Yukon Coastal Plain (NW Canada) during the past three centuries. *The Holocene* 27: 1846-1858.

Xu L, Myneni RB, Chapin III FS, *et al*. (2013) Temperature and vegetation seasonality diminishment over northern lands. *Nature Climate Change* 3: 581-586.

Yu Z, Loisel J, Charman DJ, *et al*. (eds) (2014) Holocene peatland carbon dynamics in the circum-Arctic region. *The Holocene* 24(9): 1021-1173.

Zhuang Q, Melillo JM, Sarofim MC, *et al*. (2006) CO_2 and CH_4 exchanges between land ecosystems and the atmosphere in northern high latitudes over the 21st century. *Geophysical Research Letters* 33: L17403.

John F Hiemstra
Department of Geography
Swansea University, UK