Available nitrogen and environmental controls on carbon exchange in a High Arctic wetland

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Abstract. Increased soil nutrient availability, and associated increase in vegetation productivity, could create a negative feedback between Arctic ecosystems and the climate system, reducing the contribution of Arctic ecosystems to future climate change. To predict whether this feedback will develop, it is important to understand the environmental controls over nutrient cycling in High Arctic ecosystems, and how they vary over space and time. This study explores the environmental controls over spatial patterns of soil nitrogen availability in a High Arctic wet sedge meadow and how it influences carbon exchange processes. Ion exchange resin membranes measured available inorganic nitrogen in soils throughout the growing season at a high spatial resolution, while environmental variables (e.g. active layer depth, soil temperature, soil moisture) and carbon flux measurements were taken at frequent intervals during the 2016 field season. Moisture variability in a seemingly homogenous wet sedge meadow allowed for the investigation of nutrient availability and carbon exchange across naturally-occurring moisture gradients. Environmental measures had strong relationships with total and late season nitrate levels (total season dry tracks nitrate R^2 = 0.533, total season wet tracks nitrate R^2 = 0.803, late season nitrate R^2 = 0.622), with soil temperatures at 5 cm depth having the greatest effect. Soil available nitrate and ammonium had strong relationships with total and early season gross primary productivity (total season wet tracks R^2 = 0.685, early season dry tracks R^2 = 0.788, early season wet tracks R^2 = 0.785). Higher ammonium concentrations coincided with greater gross ecosystem productivity. Nitrate concentrations correlated strongly to soil moisture, but nitrate levels were much lower than ammonium concentrations, suggesting low rates of nitrification. Similar patterns were observed regardless of whether the wet-sedge meadow was classified as wet or dry, but the relationships were always stronger in areas classified as wet, indicating the importance of moisture and water availability on abiotic processes in this High Arctic wet sedge meadow. Inclusion of inorganic nitrogen availability in multiple regression models of productivity and respiration increased the predictive strength of these models compared to using environmental variables alone. These results suggest that finer scale processes altering nitrogen availability may influence the overall carbon balance of wet sedge meadows in the High Arctic, and influence how these ecosystems respond to changes in climate.

1 Introduction

Warming temperatures in the High Arctic are expected to exceed global rates by 40% (IPCC, 2013). Changes in seasonal weather patterns may also influence ecosystem-level abiotic factors, which in turn will influence biogeochemical processes (e.g. carbon (C) and nitrogen (N) cycles) in complex ways. Some of the consequences of Arctic climate change include increased air temperatures leading to earlier snowmelt onset (Young, 2006) and precipitation increase leading to permafrost degradation and the release of previously unavailable soil C (Oechel *et al.*, 1993; Schuur *et al.*, 2009). Warming is expected to accelerate the decomposition of soil organic matter (SOM) (Chapin *et al.*, 1995; Aerts *et al.*, 2005; Bell *et al.*, 2013), potentially altering rates of nutrient cycling. Nitrogen fixation by key ecosystem species like *Nostoc commune* and *Sphagnum spp.* will also change with air temperature increases (Chapin *et al.*, 1995; Schmidt and Lipson, 2004), potentially altering available nutrient pools. In turn, higher nutrient availability could alter species composition within High Arctic ecosystems (Aerts *et al.*, 2005), plant productivity (Shaver *et al.*¸ 2000), and the net C balance (Welker *et al.*, 2004). Some of these changes are already occurring with warming (Bintanja and Andry, 2017), and further changes are expected. The trajectory of environmental change in the Arctic will depend on whether Arctic ecosystems respond through positive or negative feedbacks. Given the number of potential changes and their interactions, an ecosystem-level understanding is critical to understand how High Arctic ecosystems will respond to future changes in climate.

High Arctic wetlands play an important role in the hydrology and ecology of Arctic environments (Grogan and Jonasson, 2005), as they are the most productive vegetation community in the High Arctic environment (Atkinson and Treitz, 2013). Wetlands require a constant, sufficient water supply, and are found where water gains exceed losses (Woo, 2011). Consequently, the availability of water in the otherwise semi-arid environment of the Arctic is a determining factor in the location and productivity of these wetlands (Woo and Young, 2006; Woo and Young, 2012). These moist areas contain unique plant species and provide sustenance for Arctic fauna (Woo and Young, 2006; Woo and Young, 2012). With changes in climate anticipated in the High Arctic, land classes such as wet sedge meadows will likely respond dramatically, and changes in these wetlands will have cascading effects on terrestrial and hydrological features around them.

Arctic wetlands also contribute significantly to the landscape-scale C balance in the High Arctic. These wetlands contain a disproportionate amount of soil C (Post *et al.*, 1982; Grogan and Chapin, 1999) and could contribute significantly to the global C balance if this carbon is released (Schuur *et al.*, 2008). It is expected that increased C losses from the terrestrial environment will result from permafrost degradation due to the changing global climate (Tarnocai *et al.*, 2009). Other research, however, has shown that High Arctic wetlands have the potential for increased productivity and C storage associated with changes in temperature and precipitation (Nobrega and Grogan, 2008; Hill and Henry, 2011). These potential increases in productivity can help offset possible soil C losses associated with permafrost thawing. Short-term studies of Arctic tundra environments suggest that Arctic permafrost regions currently act as sinks of atmospheric and terrestrial C (Nobrega and Grogan, 2008; Lafleur *et al.*, 2012; McGuire *et al.*, 2012); however, the comprehensive C study by McGuire *et al.* (2012) also determined that the tundra has been C neutral in recent decades. Generally, long-term C studies are still lacking across the High Arctic tundra (Euskirchen *et al.*, 2016). A long-term study by Euskirchen *et al.* (2016) found that increases in air and soil temperatures at multiple depths may trigger a new trajectory of CO_2 release. In addition, global climate models by Avis *et al.* (2011) have projected that permafrost degradation can lead to a decrease in the areal extent of wetlands, decreasing their contribution to the landscape-scale C balance in the High Arctic. More research is needed to understand the relationship between climatic warming and Arctic wetland structure and function to determine their future contribution to climate warming.

The balance between ecosystem respiration (ER) and gross primary productivity (GPP) determines the net terrestrial C balance. Arctic wetlands have long been regarded as C sinks due to the dominance of GPP over ER (Mikan, *et al.*, 2002; Nobrega and Grogan, 2008; Lafleur *et al.*, 2012; McGuire *et al.*, 2012). However, warming temperatures are expected to increase ER in the Arctic, which could lead to a shift in the C balance depending on the response of GPP; this could lead to decreased net C storage and make permafrost regions net C sources (Welker *et al.*, 2004; Commane *et al.*, 2017). Belowground CO_2 release is season-dependent and strongly influenced by climate (Grogan and Chapin, 1999; Sullivan *et al.*, 2008), and High Arctic wetlands may respond more rapidly due to the limited temperature ranges of high latitudes. Studies at Toolik Lake, Alaska found that simulated warming made wet sedge tundra plots a weak sink for CO_2 at the peak of the growing season, but only for a short period of time (Johnson *et al.*, 2000). Similarly, a study that included a Canadian High Arctic wetland at Alexandra Fiord on Ellesmere Island showed that a wet sedge meadow was a net CO_2 source until switching to a sink closer to the end of the growing season (Welker *et al.*, 2004). Most of the previously mentioned studies did not consider how changes in nutrient availability might influence ecosystem C balance.

Changes in climate could also influence N cycling processes, with consequences for the net C balance (Chapin *et al.*, 2002; Mack *et al.*, 2004). It is important, therefore, to consider how climate change will alter microbial controls on N cycling. Mikan *et al.* (2002) found that warming in laboratory incubation studies stimulated microbial activity and increased nutrient availability in thawed soils. Microbial activity is known to remain active throughout the winter season, and can contribute significantly to nutrient budgets during spring thaw (Hobbie and Chapin, 1996; Schmidt and Lipson, 2004; Edwards *et al.*, 2006). Because the insulating snow layer prevents Arctic mid-winter soils from falling below -10°C (Clein and Schimel, 1995), the occurrence of freeze-thaw events allows microorganisms to remain active as long as pockets of liquid water are still present as a result of the snow insulation (Edwards *et al.*, 2006). The activity of these microorganisms will mobilize N stores that can help mitigate the current nitrogen limitation in High Arctic ecosystems (Mikan *et al.*, 2002), promoting plant production and soil respiration in the following growing season. In High Arctic wetlands, where microbial metabolism is primarily anaerobic due to the anoxic conditions, changes to drainage, precipitation, or evapotranspiration patterns will be the primary driver of microbial activity changes in the future (Mikan *et al.*, 2002; Zamin *et al.*, 2014).

Future warming could alter interactions between C and N cycles in the High Arctic. Warming will lead to a deeper active layer, lower water table, and promotion of subsurface flow pathways and water availability that enhances nutrient release from decomposing organic matter (Biederbeck and Campbell, 1973; Billings *et al.*, 1982; Nadelhoffer *et al.*, 1991; Johnson *et al.*, 2000; Natali *et al.*, 2011). These factors in turn affect other abiotic characteristics such as soil moisture (SM) and pH, which have a strong impact on both C and N cycling processes. High Arctic plant growth is typically limited by N availability (Nadelhoffer *et al.*, 1992; Shaver and Chapin, 1995; Shaver *et al.*, 2000). While Arctic plant growth is typically slow, relative to more productive, nutrient-rich temperate environments, tundra environments are more responsive to short-term (1-10 year) changes in nutrient availability (Shaver *et al.*, 2000). Due to the interconnected nature of the physical environment and microbial processes, it is expected that changes in nutrient availability will influence C exchange with the atmosphere. In tundra microcosms (Billings *et al.*, 1984), increased soil N significantly increased CO_2 uptake. Decomposition of SOM as a result of warmer soils can release plant-available N forms, enhancing plant growth and ecosystem productivity (Hill and Henry, 2001; Weintraub and Schimel, 2005). Other research has demonstrated the importance of environmental variability on C exchange in High Arctic ecosystems (Blaser, 2016). This study explores the relationships between environmental variables and C and N cycling processes to determine the spatial and temporal extent of these relationships in the CBAWO wetlands.

In this study, we characterize the spatial and temporal patterns of available soil N in a wet sedge meadow in the Cape Bounty Arctic Watershed Observatory of the Canadian High Arctic, how they relate to environmental variability, and the consequences for C exchange processes. Many factors determine the levels of plant-available N that fuel N cycling and C flux (Nadelhoffer *et al.*, 1991; Clein and Schimel, 1995; Chapin *et al.*, 2002), and the need to understand the relationship between the environmental variables and these processes is more important than ever in a rapidly changing climate. Previous studies in this wet sedge meadow have looked at the seasonal variability of C exchange processes and environmental variables across wet and dry areas within wet-sedge meadows (Blaser, 2016). However, the relationships between environmental variables, available N, and C exchange have not been assessed.