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THERMOKARST AND WILDFIRE: EFFECTS OF DISTURBANCES RELATED TO
CLIMATE CHANGE ON THE ECOLOGICAL CHARACTERISTICS AND FUNCTIONS OF
ARCTIC HEADWATER STREAMS

A Dissertation Presented

by

Julia R. Larouche

to

The Faculty of the Graduate College

of

The University of Vermont

In Partial Fulfillment of the Requirements
for the Degree of Doctor of Philosophy
Specializing in Natural Resources

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ABSTRACT

The Arctic is warming rapidly as a result of global climate change. Permafrost – permanently frozen ground – plays a critical role in shaping arctic ecosystems and stores nearly one half of the global soil organic matter. Therefore, disturbance of permafrost will likely impact the carbon and related biogeochemical processes on local and global scales. In the Alaskan Arctic, fire and thermokarst (permafrost thaw) have become more common and have been hypothesized to accelerate the hydrological export of inorganic nutrients and sediment, as well as biodegradable dissolved organic carbon (BDOC), which may alter ecosystem processes of impacted streams.

The biogeochemical characteristics of two tundra streams were quantified several years after the development of gully thermokarst features. The observed responses in sediment and nutrient loading four years after gully formation were more subtle than expected, likely due to the stabilization of the features and the dynamics controlling the hydrologic connectivity between the gully and the stream. The response of impacted streams may depend on the presence of water tracks, particularly their location in reference to the thermokarst and downslope aquatic ecosystem. We found evidence of altered ecosystem structure (benthic standing stocks, algal biomass, and macroinvertebrate composition) and function (stream metabolism and nutrient uptake), which may be attributable to the previous years' allochthonous gully inputs. The patterns between the reference and impacted reaches were different for both stream sites. Rates of ecosystem production and respiration and benthic chlorophyll-a in the impacted reaches of the alluvial and peat-lined streams were significantly lower and greater, respectively, compared to the reference reaches, even though minimal differences in sediment and nutrient loading were detected. Rates of ammonium and soluble reactive phosphorus uptake were consistently lower in the impacted reach at the alluvial site. The observed differences in metabolism, nutrient uptake and macroinvertebrate community composition suggest that even though the geochemical signal diminished, gully features may have long-lasting impacts on the biological aspects of downstream ecosystem function.

In a separate study, a suite of streams impacted by thermokarst and fire were sampled seasonally and spatially. Regional differences in water chemistry and BDOC were more significant than the influences of fire or thermokarst, likely due to differences in glacial age and elevation of the landscape. The streams of the older (>700 ka), lower elevation landscape contained higher concentrations of dissolved nitrogen and phosphorus and DOC and lower BDOC compared to the streams of the younger (50-200 ka) landscapes that had lower dissolved nutrient and DOC quantity of higher biodegradability. The findings in this dissertation indicate that arctic stream ecosystems are more resilient than we expected to small-scale, rapidly stabilizing gully thermokarst features and disturbance caused by fire. Scaling the results of these types of studies should consider the size of thermokarst features in relation to the size of impacted rivers and streams. It remains to be determined how general permafrost thaw will affect the structure and function of arctic streams in the future.

CITATIONS

Material from this dissertation has been submitted for publication to Journal of Geophysical Research Letters Biogeosciences on September 9, 2014 in the following form:

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DEDICATION

For Ted and Michael Leaf, each equally my love and joy.

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Throughout this endeavor I have received support and encouragement from a great number of individuals. I would like to express my deep appreciation and gratitude to my advisor, Dr. William ‘Breck’ Bowden, for the mentorship and encouragement he provided me from my first trip to Alaska a decade ago, through to completion of this degree. His guidance has made this a thought-provoking and rewarding journey; his love for science and the field of arctic ecology is truly an inspiration to many.

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CHAPTER 1: BACKGROUND

1.1 Introduction

The Arctic is an important region to study for numerous reasons, including but not limited to: 1) its vulnerability to global climate feedbacks due to amplified mechanisms (Serreze and Barry 2011); 2) its capacity for both carbon storage and potential release from permafrost (Grosse et al. 2011, Schuur et al. 2008, Tarnocai et al. 2009); and 3) its significant contribution of riverine dissolved organic matter to the Arctic Ocean (Frey and McClelland 2009). The Arctic is projected to warm considerably in the next 100 years and therefore, the consequent ecological responses of arctic ecosystems is critically important for predicting the impacts of a changing climate, in order to employ adaptive management strategies (Chapin et al. 2006).

This dissertation research quantifies the response of arctic stream ecosystems to permafrost thaw within the context of a National Science Foundation (NSF) funded ARCTic System Science Thermokarst (ARCSS/TK) collaborative research project entitled: *Spatial and Temporal Influences of Thermokarst Failures on Surface Processes in Arctic Landscapes*. The objective of the ARCSS/TK project was to improve our understanding of how degradation of permafrost due to climate warming will affect the arctic landscape. To that end, the ARCSS/TK project included collaborative components that focused on: plant community composition and succession; distribution and processing of soil nutrients; trace gas exchanges; and hydrologic export of sediments and nutrients. The research presented in this dissertation addresses how disturbance regimes associated with climate change (e.g., permafrost thaw and fire) affect the biogeochemical

characteristics and function of arctic tundra headwater streams on both local and regional scales within Arctic Alaska.

1.2 Disturbance in the Arctic

Disturbance regimes in ecology can be placed within the context of press versus pulse dynamics (Collins 2007). Press disturbances are slow and persistent, occurring on the decadal to century time scales, whereas pulse disturbances are short-term and catastrophic in nature. The proposed work encapsulates the overarching *press* disturbance of climate change in the Arctic (e.g., increased air temperatures and precipitation) and its interaction between fire as a *pulse*, both of which likely affect soil temperatures and permafrost degradation (*press*). An extreme manifestation of permafrost degradation is thermokarst formation, another *pulse* disturbance of interest in permafrost dominated landscapes. This research explores the effects of permafrost disturbance on stream biogeochemistry via three interactive disturbance lenses: climate change, wildfire, and thermokarst formation, in which the latter two are considered pulse dynamics that are immediate and more observable in nature compared to the former.

Disturbance in arctic and boreal ecosystems is expected to escalate in response to future changes in climate. Examples of physical responses to climate change in northern Alaska include the deepening of the seasonally-thawed surface soil or active layer (Shiklomanov et al. 2010), permafrost warming (Romanovsky et al. 2011), permafrost collapse (Belshe et al. 2013, Jorgenson et al. 2006), and wildfire (Jones et al. 2009, Randerson et al. 2006). There is evidence of recent increases in permafrost disturbance (Balsler et al. 2014, Gooseff et al. 2009) on the North Slope of Alaska and wildfire has the potential to become a major disturbance factor in the tundra region (Higuera et al. 2011,

Rocha et al. 2012). The proposed research quantifies the effects of disturbances to permafrost on stream biogeochemistry via three interactive disturbance lenses: climate change, wildfire, and thermokarst formation, in which the latter two are considered pulse dynamics that are immediate and more observable in nature compared to the former (Fig. 1).

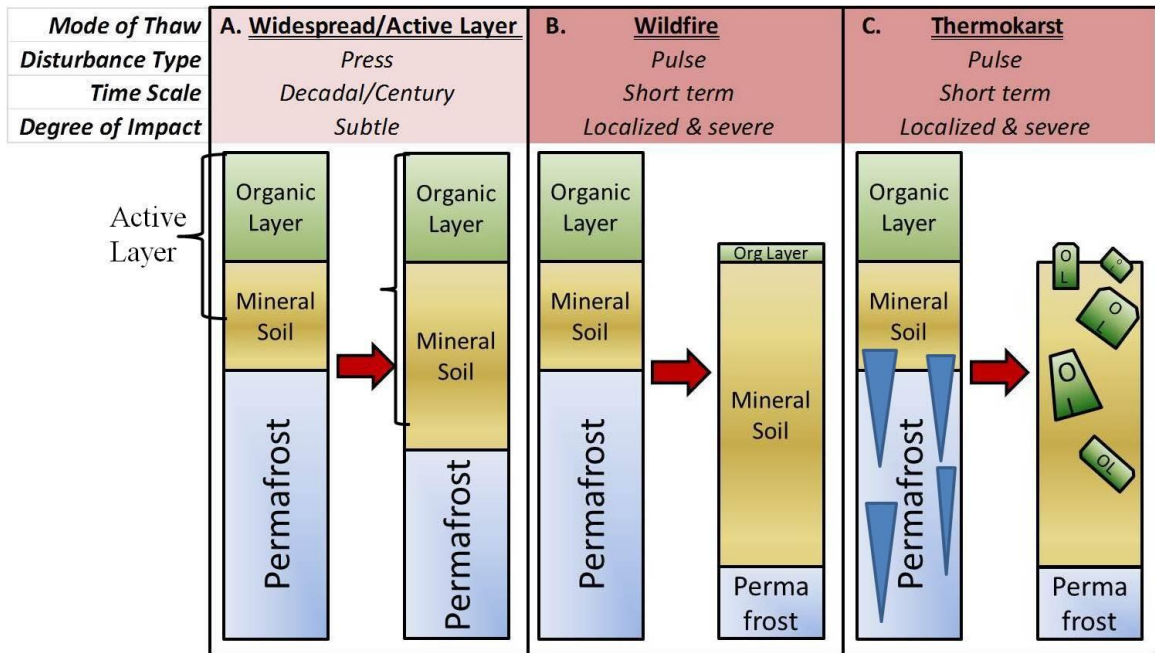


Figure 1. Three forms of permafrost thaw via different mechanisms categorized by the press-pulse disturbance regime: A. widespread loss of permafrost extent and active layer deepening; B. wildfire induced permafrost thaw results in combustion of insulating organic layer mat; and C. thermokarst is an extreme mode of permafrost degradation resulting in upheaval and redistribution of organic and mineral layers, typically downslope to aquatic ecosystems. This research focuses on B and C.

1.2.1 Climate change in the Circum-Arctic watershed.

Research has shown clear evidence that high latitude air temperatures are increasing at a rate nearly twice as large as the global average – a phenomenon known as ‘Arctic amplification’ (Screen and Simmonds 2010a, b, Serreze and Barry 2011, Serreze and Francis 2006) – largely due to feedbacks associated with sea-ice loss and decreasing

snow cover (ACIA 2005, AMAP 2011, Parmentier et al. 2013). Warming has been the most severe (1.6°C per decade) during autumn and winter (AMAP). Many key climate drivers in the Arctic region are projected to change dramatically in the next 100 years: rising air temperatures (3-5°C annually and 4-7°C in winter) (Fig. 2); increases in precipitation (20-30%) as rainfall (Manabe and Stouffer 1993, Screen and Simmonds 2012) (Fig. 3); and changes in the extent and severity of arctic wildfires (Hu et al. 2010a, Kasischke and Turetsky 2006). There is some debate over the projected frequency and severity of fire in the Arctic. Figure 4 shows the occurrence of fire by decade in Alaska. Although fire is a common disturbance in the subarctic, boreal forest region of Alaska, fires may become more common in the arctic tundra region north of the Brooks Range, where historically wildfire has been rare. There is some evidence of increased detection of fires in this region from lightning strikes (Miller, 2010).

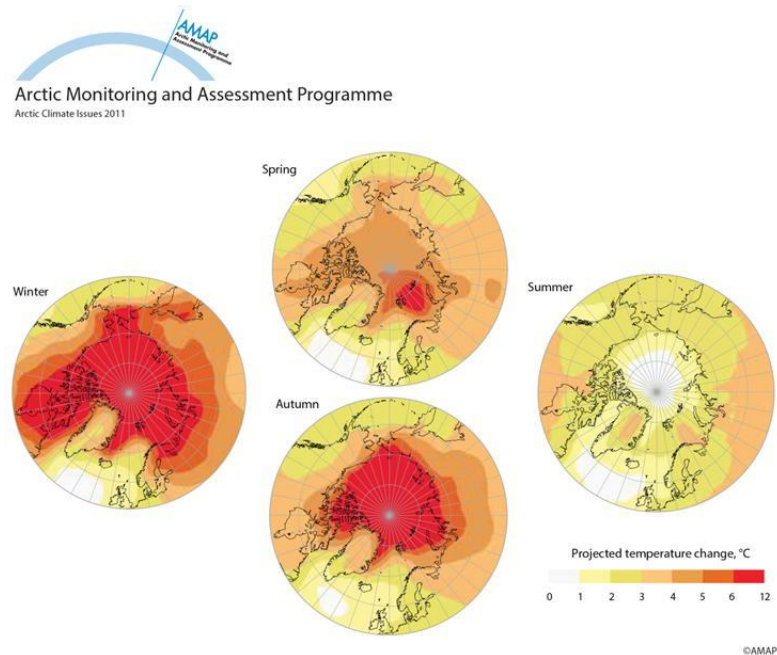


Figure 2. Projected surface air temperature changes (°C) in the northern latitudes for each season by 2100 based on the departure from mean temperatures between 1950-2000 (AMAP 2011).

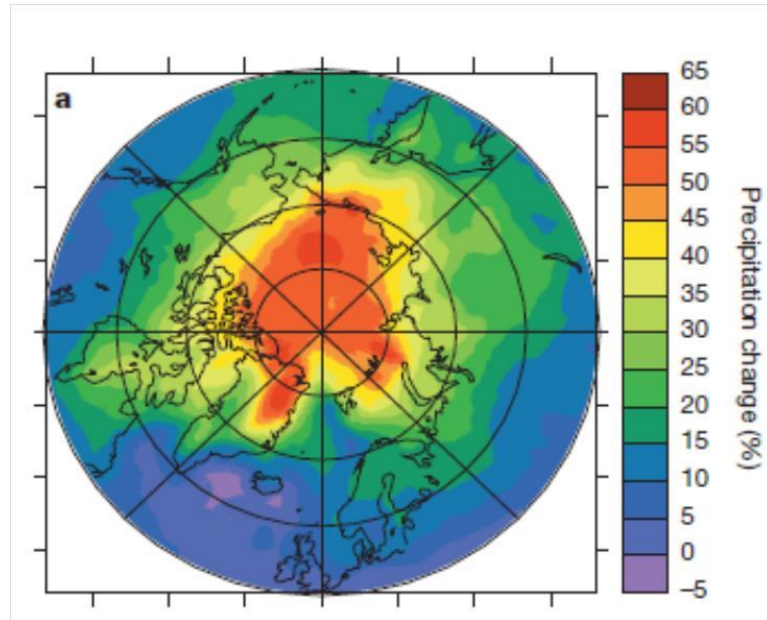


Figure 3. Geographical distribution of simulated annual mean 21st-century precipitation in the Arctic region. Changes (based on the difference between the means over 2091-2100 and 2006-2015) in precipitation (%) (Bintanja and Selten 2014).

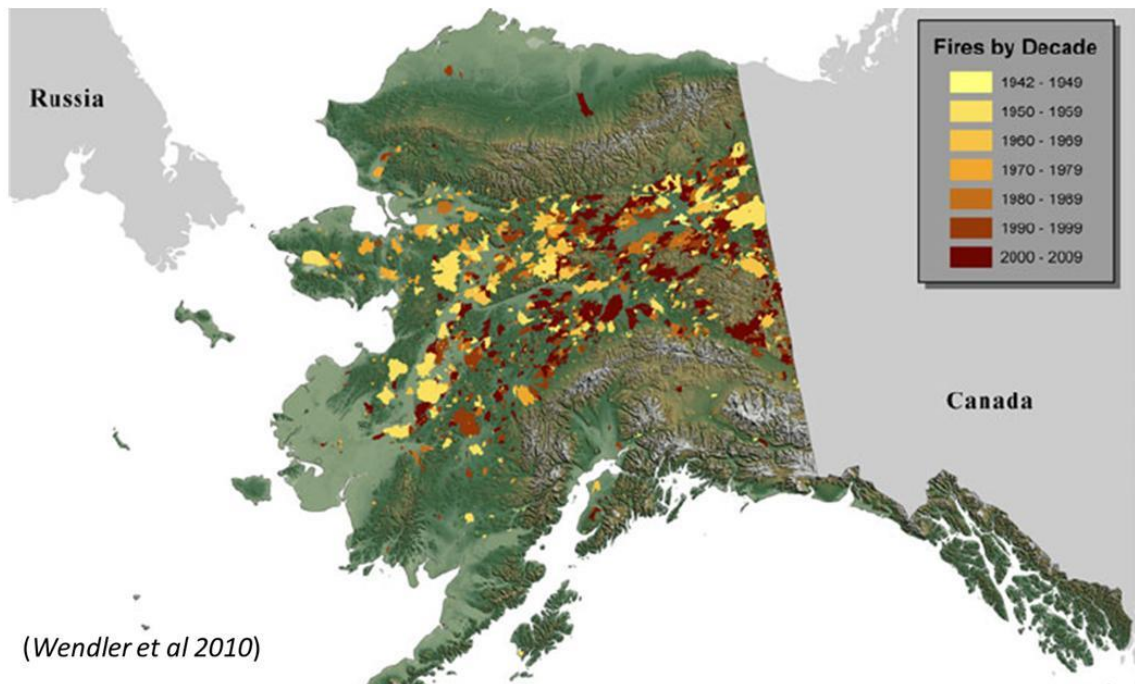


Figure 4. Area burned in Alaska over more than the last half century. Note that very large portion of the Interior of Alaska has been affected. Fire occurrence on the North Slope has been historically rare, but may be increasing in frequency due to lightning strikes (Wendler et al 2010).

The discharge and biogeochemistry of arctic rivers and streams are particularly sensitive indicators of both aquatic and terrestrial change within the circumarctic watershed (Holmes et al. 2000). An intensification of the freshwater cycle is projected across the arctic region with changes in the quantity of water (i.e., increases in precipitation, evapotranspiration, storage, and discharge) (Peterson et al. 2002, Peterson et al. 2006, Rawlins et al. 2010), but considerably less is known about the quality of water (i.e., the magnitude and change of riverine water chemistry and dissolved organic matter fluxes) at the pan-arctic scale (Holmes et al. 2012). Headwater tundra streams are of particular interest because they often carry remarkably high organic matter loads (Peterson et al. 1986).

1.2.2 Permafrost and its degradation.

Permafrost – permanently frozen ground – underlies 16% of global soil but contains more than half of the global soil organic matter (SOM), consisting of 1,400-1,800 petagrams (Pg) of carbon (Tarnocai et al. 2009) and 70-80 Pg of nitrogen (Weintraub and Schimel 2003). The permafrost zone comprises 25% of the land area in the Northern Hemisphere and is divided into different zones based on the underlying extent of frozen ground: continuous (>90%), discontinuous (50-90%), sporadic (10-50%) and isolated (<10%). These zones occupy 47%, 19%, 17% and 17% of the entire permafrost region, respectively (Brown and Romanovsky 2008). Continuous internal permafrost temperatures within the foothills of the Brooks Range on the North Slope of Arctic Alaska ranges between -2°C and -5°C and can be up to 200 meters thick.

Permafrost soils are unique since they contain vast stores of soil organic matter. Due to low rates of primary productivity and cold, wet conditions limiting

decomposition, the arctic region has been a carbon sink for the past 10,000 years (Hicks Pries et al. 2012), but has the potential to become a carbon source (Oechel et al. 1993). The permafrost carbon feedback is the amplification of warming due to greenhouse gas emissions (carbon dioxide and methane) from thawing permafrost (Schaefer et al. 2014) and is considered the largest terrestrial feedback associated with climate change, as well as the one most likely to occur as a tipping point (Lenton 2012, Schuur et al. 2008). The response of arctic ecosystems, in particular the permafrost and the pool of soil carbon, to climate forcing has direct bearing on local and global scale elemental cycling, although the timing and magnitude remains unquantified.

Permafrost and active layer dynamics impart fundamental controls on the structure and function of the arctic landscape such as drainage and hydrologic flowpaths (McNamara et al. 1997); vegetation (Mack et al. 2004); and soil moisture (Zhang et al. 1997). Permafrost in arctic and subarctic regions influences key geomorphic and ecological processes in tundra and boreal forests (Jorgenson and Shuur 2009, Jorgenson et al. 2001). Hydrobiogeochemical factors (e.g., hydrology, biota, substrate) in the Arctic are shaped by various constraints inherent to northern latitudes including: low air, water and soil temperatures; low precipitation; low year-round light availability and the presence of permafrost. Any disturbance to the permafrost regime whether small or large scale, gradual or episodic, may therefore, have significant impacts on the ecology of arctic ecosystems and vice versa through complex feedback loops (Jorgenson et al. 2010).

The observed and projected trends of these aforementioned key climatic drivers (i.e., rising air temperatures and affiliated increases in precipitation and wildfire) and their interactions is the manifestation of a 'progressive increase in the continentality of

climate' (French 2007), which is to say that a greater range of soil temperatures will result from an overall thermal disequilibrium of surface and subsurface arctic landscapes. Primary consequences of increasing soil temperatures include the thaw and degradation of permafrost. Permafrost degradation refers to widespread permafrost thaw resulting in an overall decrease in permafrost extent and depth and a thickening of the active layer – defined as the layer of ground subject to annual thawing and freezing in areas underlain by continuous permafrost (Kane et al. 1991). Long term records from borehole monitoring across northern latitudes show a significant warming trend of near-surface permafrost in the past 30 years across the Circum-Arctic (Fedorov 1996, Jorgenson et al. 2001, Osterkamp et al. 2000, Romanovsky et al. 2002). Warming has increased permafrost temperatures by 2°C on average across different parts of the permafrost zone in northern regions (Frauenfeld et al. 2004, Isaksen et al. 2001, Oelke and Zhang 2004, Osterkamp and Romanovsky 1999, Zhang et al. 1997) leading to permafrost degradation and thaw, both observed (Jorgenson et al. 2006) and projected (Grosse et al. 2011, Hugelius et al. 2011).

1.2.3 Thermokarst.

Permafrost degradation can be categorized by the time scales on which they occur using the 'press' and 'pulse' framework (Collins 2007). Press disturbances are slow and persistent occurring on the decadal to century time scales and include the widespread top-down thawing of the permafrost and the deepening of the active layer. In contrast, pulse disturbances are short-term and episodic in nature and include thermokarst processes (Brouchkov et al. 2004). Thermokarst formation is the subsidence and collapse of soil structure resulting from ground-ice melt (Davis 2001), specifically when ground ice

volume exceeds soil pore space (Kokelj and Jorgenson 2013). The primary causes of thermokarst are: high quantity of ground ice; the presence of surface water; fluvio-thermal erosion (Romanovskii 1961), and wildfire (Brouchkov et al. 2004, French 2007). The general use of the term 'thermokarst' encompasses numerous thermo-erosional features of different morphological types controlled by various ecological factors such as slope and position on landscape; soil texture; ice morphology and content; presence of surface water and subsurface flow path movement; vegetation, etc. (Jorgenson and Osterkamp 2005, Jorgenson et al. 2008). In upland arctic landscapes there are three common geomorphic types of thermokarst features: retrogressive thaw slumps, active-layer detachment slides, and thermo-erosional gullies (Kokelj and Jorgenson 2013). Retrogressive thaw slumps, which are found primarily on steeper, south and south-east facing slopes of river banks and lake shorelines, are caused by lateral fluvio-erosive forces acting preferentially along ice wedges of river banks (Lantuit and Pollard 2008). Active-layer detachment slides form when an ice-rich transition zone provides a slippery surface for seasonally thawed vegetation and soil to move downslope (Jorgenson et al. 2010). Thermo-erosion gullies form when ice wedges melt, often due to erosion from flowing water or following surface disturbance (Bowden et al. 2008, Godin and Fortier 2012, Shuur et al. 2004). Formation of thermo-erosional features is associated with extreme warm or wet summer conditions (Balsler et al. 2014, Lamoureux and Lafrenière 2009, Lewkowicz 2007) and fluvial erosion from rivers and lakes (Kokelj et al. 2009). The period of time these features remain active vary by morphological type. Thaw slumps remain active on the decadal time scales (Lewkowicz 1987), while active-layer detachments can form suddenly over a period of hours to weeks (Lewkowicz 2007) and

stabilize rapidly within a few seasons (Lafrenière and Lamoureux 2013). The limited observations of gully thermokarst features indicate that these types initiate, evolve, and stabilize within a decade (Bowden et al. 2014).

These three morphologies influence approximately 1.5% of the total landscape in the northern foothills of the Brooks Range, Alaska with the gullies being the most prevalent (54% of detected features), followed by active-layer detachments (30%) and thaw slumps (16%) (Krieger 2012). Recent evidence has pointed to accelerated rates of thermokarst activity with a 3.5-8.0% average increase in the areal extent of thermokarst degradation in the last 50 years in Alaska (Jorgenson and Shuur 2009) and a projection of 20-50% of upland area in the continuous permafrost zone by 2100 (Slater and Lawrence 2013, Zhang et al. 2000).

1.2.4 Wildfire.

Future warming is expected to increase the frequency and severity of wildfire in the sub-Arctic (Chapin et al. 2008, Flannigan et al. 1998) and occurrence of lightning-driven fires in the Arctic (Hu et al. 2010b, Kasischke et al. 2010). Post-fire conditions can promote further degradation of permafrost (Burn 1998, Yoshikawa et al. 2002) as a result of changes in organic layer depth, albedo, and vegetation, which all lead to the disruption of the thermal regimes of permafrost soils. Fire in arctic and subarctic regions leads to a deepening of the active layer (Burn 1998) for decades post-fire (Rocha et al. 2012); changes in carbon exchange (O'Donnell et al. 2011, Rocha and Shaver 2010) and shifts in dominant forest cover (Barrett et al. 2011) and fungal community composition (Hewitt et al. 2013). Fire has also been documented as a driver for thermokarst initiation (Agafonov et al. 2004, Katamura et al. 2009, Osterkamp et al. 2000, Shuur and Jorgenson 2004) and

features have been observed in the Anaktuvuk River Fire area likely due to the removal of the insulating organic mat protecting the permafrost post-fire (field observations).

Fire severity also plays an important role in the hydrological response to disturbance. Severe fires can burn through the entire insulating moss layer of the tundra, resulting in permafrost degradation and subsequent alterations to flow paths and hydrologic connectivity to mineral layers (Hinzman et al. 2005). Burned conditions in lower latitudes convert organic plant biomass pools into inorganic nutrient pools that are susceptible to export downslope to aquatic ecosystems (Mast and Clow 2008, Rhoades et al. 2011). Effects of fire on aquatic biogeochemistry are well quantified in lower latitudes and temperate zones and include: increased water runoff (Sheridan et al. 2007); sediment losses (Noske et al. 2010, Rulli and Rosso 2005); and increased concentrations of major ions and nutrients in soil and stream water (Bayley et al. 1992a, Bayley et al. 1992b, Chorover et al. 1994). In the boreal forest of Alaska, stream DOC concentration declined following a wildfire, presumably due to loss of microbial biomass (Betts and Jones 2009, Petrone et al. 2007, Schindler et al. 1997) and bioavailable dissolved organic matter in streams decreased post-fire and during thermokarst formation (Balcarczyk et al. 2009).

1.3 Consequences of Disturbance on Aquatic Biogeochemistry

Given the projected dramatic hydrological shift in the Arctic due to varying modes of permafrost degradation, a change in nutrient, solute and sediment exports are expected and have been observed (Frey and McClelland 2009) primarily due to the breach in the permafrost barrier that characteristically confines surface flow paths through the organic-rich active layer (Carey and Quinton 2004). As permafrost degrades, changes in carbon and nutrient export via rivers and streams may result from changes in

hillslope water flowpaths and/or microbial activity but the nature of the responses are potentially contradictory (Frey and McClelland 2009). Some studies predict increases in riverine export of terrestrial organic matter and associated nutrients due to thawing of organic-rich permafrost (Frey and Smith 2005) and/or due to enhanced productivity and decomposition in tundra soils following thaw (Shaver et al. 1992), driving the overall system toward a carbon sink or source depending on the comparative responses of these two important terrestrial processes (Schuur et al. 2009). Other studies suggest that organic matter and nutrient export will decrease as permafrost thaws due to deepening of the active layer and altered water flowpaths within the soil matrix, either because organic matter is trapped in newly thawed mineral soils or respired during longer residence times (Petroni et al. 2007, Striegl et al. 2005). Longer flow paths and interaction with deeper mineral layers may result in an increase or decrease in elemental fluxes to streams. Increased elemental export may occur due to leaching and release of the vast amount of carbon, weathered solutes, and nutrients contained in permafrost (Michaelson et al. 1996) and increased nitrogen mineralization under warming conditions (Harms et al. 2014, Jones et al. 2005a, Shaver et al. 1992); whereas decreases in elemental fluxes may occur due to nutrient adsorption and microbial uptake in deeper soils. Flow dynamics through hillslope thermokarst disturbance adds an additional layer of complexity as exposed, heterogeneous scars impart a new biogeochemical signature to hillslope waters upon entering receiving streams (Bowden et al. 2008).

Investigations of aquatic responses to permafrost thaw and degradation have taken four primary approaches: 1) sampling lakes and rivers over time on various landscape scales to quantify the impact of widespread, gradual thaw (McClelland et al. 2007,

Townsend-Small et al. 2011); 2) sampling watersheds of differing permafrost extent to determine if changes in elemental budgets are related to the distribution of permafrost (Frey et al. 2007, Jones et al. 2005b, Petrone et al. 2006); 3) sampling paired reference and disturbed (by fire or thermos-erosion) watershed outlets or lakes to determine if disturbance can outweigh other environmental and landscape factors that typically drive variation in water quality (Burn et al. 2009, Kokelj et al. 2005); and 4) sampling upstream and downstream of a thermokarst disturbance (sporadically or seasonally within and across seasons) in lotic systems (Bowden et al. 2008).

1.3.1 Sediment and nutrients.

One of the more striking consequences of hillslope thermokarst disturbance is the sheer volume of material, or mass-wasting, that can be delivered as sediment from thermokarst features to receiving aquatic systems, particularly with sizeable retrogressive thaw slumps (Calhoun 2012, Kokelj et al. 2013). One thermokarst gully that formed in 2003 and intersected a small, headwater beaded-stream (the Toolik River) in a 0.9 km² catchment in Alaska delivered more sediment downslope to the river than is normally delivered in 18 years from a 132 km² adjacent reference catchment of the upper Kuparuk River (Bowden et al. 2008). While smaller features such as active-layer detachment slides and gullies have the potential to generate substantial sediment loads downstream immediately after formation (Bowden et al. 2008, Lamoureux and Lafrenière 2009), the longevity of the export remains unclear. A multi-year study on the impact of active-layer detachments by Dugan et al. (2012) suggests that large downstream lakes may have the potential to buffer the impact of significant fluvial sediment loads.

1.3.2 Dissolved solutes and inorganic nutrients.

Several recent studies have shown that upland thermokarst disturbances can lead to increased concentrations and export of important inorganic nutrients (Bowden et al. 2008, Gooseff et al. 2009, Harms et al. 2014, Kokelj et al. 2005). Few studies have quantified the export to receiving waters at a catchment scale. An emerging theme in the assessment of aquatic impacts of thermokarst on the local scale is that the magnitude of exported material depends largely on thermokarst size, type, duration of activity, and hydrologic connectivity (Abbott et al. 2014, Lafrenière and Lamoureux 2013, Lewis et al. 2012). For instance, thermokarst features potentially could mobilize substantial amounts of sediments and nutrients that are not delivered to downslope aquatic ecosystems and instead retained along the hillslopes or in the riparian zone. Consequently, although thermokarst have the potential to alter hillslope hydrology and the release of terrestrial solute and nutrient stores into downslope aquatic ecosystems, neither the spatial nor temporal extent of the impacts of these changes is well understood. Some studies have observed long-lasting impacts on surface water chemistry due to legacy effects of the disturbance. In a study where thermokarst occupied approximately 2% of the catchment area, lake water quality remained affected for several decades after feature stabilization (Kokelj et al. 2005). Conversely, others have found that the impacts of disturbance disappear within a season, likely due to the rapid stabilization of active layer detachment slides (Lafrenière and Lamoureux 2013) or that the impacts of permafrost disturbance are outweighed by other driving factors such as inter-annual rainfall variability and topographic differences between monitored catchments (Lewis et al. 2012). Recent work has made the distinction that unlike shallow permafrost disturbances (e.g., gullies and

active layer detachments), thaw slump features expose deep layers of permafrost that can impact downstream geochemistry at the 10^2 km² watershed scale (Malone et al. 2013).

1.3.3 Dissolved organic carbon (DOC) quantity and biodegradability.

The Arctic Ocean represents 1% of the world's ocean water by volume, yet it receives 10% of the global river discharge and terrestrially-derived dissolved organic matter (Dittmar and Kattner 2003). This pattern exists because the six largest arctic rivers transport and process a large amount of dissolved organic matter originating from the world's largest and most vulnerable reserve of soil organic carbon. The nature of riverine dissolved organic matter (typically measured as DOC) sloughing from arctic watersheds in terms of concentration, fluxes, lability or biodegradability (relative reactivity), and age are important areas of study in order to predict the consequences of warming permafrost on elemental cycling and transport (Figure 5). It has long been assumed that riverine DOC in the Arctic is relatively recalcitrant, or biologically unavailable (Amon 2004, Rachold et al. 2004) but recent studies suggest a more labile (Uhlířová et al. 2007) and older (Dutta et al. 2006) fraction than previously thought could potentially be mobilized from thawing permafrost soil stores to streams and rivers for further processing and transport.

Recent work has shown that DOC in thermokarst outflow is highly biodegradable (Pautler et al. 2010, Vonk et al. 2013, Woods et al. 2011), though biodegradability returns to pre-disturbance levels once features stabilize (Abbott et al. 2014). Cory et al. (2014) found that the majority of DOC (70-95%) transferred from soils through surface waters (e.g., headwater streams, rivers and lakes) in the Arctic simply undergoes photolysis to CO₂ (i.e., some combination of photo-mineralization and partial photo-oxidation), rather

than bacterial respiration (i.e., biological mineralization). Therefore, there is strong evidence that highly biodegradable DOC from active thermokarst features may be processed in transit from the hillslope (Abbott et al. 2014), particularly if the flow paths are exposed to light (Cory et al. 2013).

Across various biomes, the composition and biodegradability of riverine DOC changes seasonally due to a tight coupling between terrestrial and aquatic ecosystems (Fellman et al. 2009, Holmes et al. 2008, Wang et al. 2012). In the Arctic, the quantity and quality of DOC is highest during snowmelt and decreases progressively through the summer (Holmes et al. 2008, Mann et al. 2012, Vonk et al. 2013). However, the majority of studies investigating arctic DOC biodegradability have focused on downstream reaches in large alluvial systems; the seasonal and spatial variation of DOC biodegradability in headwater streams is largely unknown. Thus, it is difficult to assess the degree to which DOC might be processed during transport from headwaters to higher order reaches.

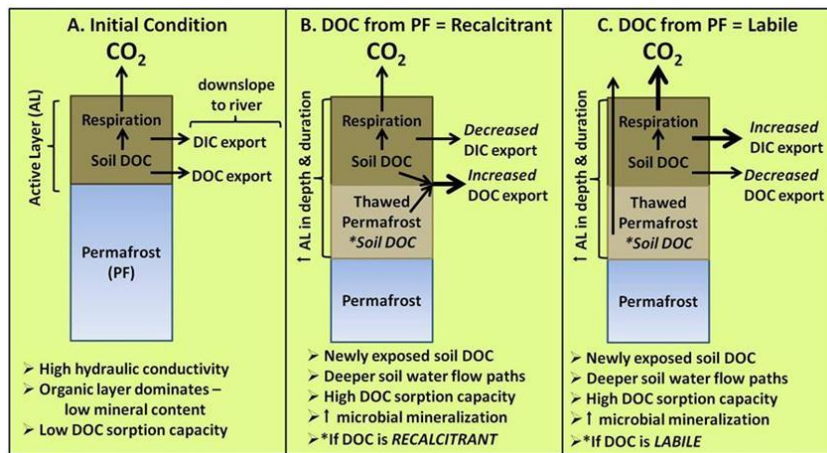


Figure 5. Proposed mechanisms of DOC dynamics under A. Initial conditions; B. if DOC from thawing permafrost is relatively recalcitrant = DOC export downslope will increase; DIC export will decrease; C. if DOC from thawing permafrost is relatively labile = DOC export will decrease and DIC export will increase (Adapted and modified from Striegl et al. 2005).

1.3.4 Potential effects of thermokarst and fire on stream function.

Regardless of the magnitude and direction of these shifts in the hydrobiogeochemical signature of arctic streams and rivers, we can expect higher order impacts to result as a consequence, particularly since productivity in these systems are related to light and nutrient availability, as well as temperature. A whole-ecosystem nutrient fertilization experiment on the Kuparuk River has shown that long-term, low-level increases in soluble reactive phosphorus alone can have important influences on benthic autotrophic and macroinvertebrate structure and significant increases in primary and secondary production (Bowden et al. 1994, Cappelletti 2006, Peterson et al. 1985, Slavik et al. 2004). Nutrient additions via export from hillslope thermokarst may enhance benthic production; however, sediment loading may offset the stimulatory effects of introduced nutrients and interfere with benthic stream structure and function. Some adverse effects of sediment influx to streams include: damage to primary producers especially from scour during storms, which can reduce primary production and ecosystem respiration; sediment can clog the streambed which reduces the connectivity between the hyporheic zone and surface waters, interfering with exchange of nutrients and dissolved oxygen (Kasahara and Hill 2006, Saenger et al. 2005); and sediment loading can also lead to instability on the stream bottom, affecting the benthic critters and their metabolism (Atkinson et al. 2008, Uehlinger and Naegeli 1998;).

Recent studies have evaluated the higher order effects of sediment and nutrient loading from thermokarst and detected significant impacts on certain aspects of the biological function of receiving waters. Lakes affected by thaw slumping in the Canadian Arctic have been shown to have significantly greater dissolved ion content, lower DOC

concentrations and increased water transparency (Thompson et al. 2008), that have in turn led to enhanced macrophyte development and higher abundance of benthic macroinvertebrates (Mesquita et al. 2010, Moquin et al. 2014) and higher abundance and diversity of periphytic diatoms (Thienpont et al. 2013). Daily rates of riverine production and respiration decreased by 63% and 68%, respectively, in the Selawik River in northwest Alaska in response to elevated turbidity levels that increased by several orders of magnitude below a massive thaw slump (Calhoun 2012). No research to date has evaluated the impact of thermokarst on benthic elemental standing stocks, metabolism and nutrient uptake in small headwater streams.

1.4 Research Questions and Hypotheses

Chapter 2. Impacts of a thermo-erosional gully on ecosystem structure and function of an arctic alluvial tundra stream, North Slope, Alaska.

Q1. How does the gully thermokarst impact ecosystem state variables (e.g., nutrient and sediment concentrations and loadings; benthic characteristics) in a downstream reach?

Q2. How does the gully thermokarst impact ecosystem processes (e.g., rates of metabolism and nutrient uptake) in a downstream reach?

Chapters 2 and 3 in this dissertation build upon the research of Bowden et al. (2008) and Gooseff et al. (2009) who sampled upstream and downstream of thermokarst impacts as an approach to test for differences in stream water quality. The primary aim was to quantify the effect of a thermokarst gully on a local scale, in a comprehensive manner on stream biogeochemistry by measuring key state and functional variables in a reference reach, upstream and downstream of the influence of a gully feature. We hypothesized that elevated sediment input from the gully thermokarst, whether persistent

or short-lived, would offset the stimulatory effects of introduced allochthonous C, N, and P on ecosystem structure and function. We expected to observe diminished quality of benthic resources (e.g., epilithic C:N:P ratios and algal biomass); reduced ecosystem production and respiration and nutrient uptake rates; and decreased macroinvertebrate richness and diversity in the Impacted stream reach.

Chapter 3. Impacts of a thermo-erosional gully on ecosystem structure and function of an arctic beaded tundra stream, North Slope, Alaska.

This study is a complement to Chapter 2 and presents the results from another stream site impacted by a gully thermokarst, of a contrasting geomorphology to the stream in Chapter 2. A similar approach was implemented to answer the same questions and hypotheses presented in Chapter 2. Both streams studied were impacted by gully features that formed five to six years prior to the start of the study. At the time we started the study, we had not anticipated the features to have reached a state of recovery.

Therefore, this work quantifies the enduring impacts of a gully on key hydrobiogeochemical variables in a comprehensive manner. Prior to this dissertation research, there was some data collected in the years immediately following the gully disturbances which can be used to assess the change in magnitude and duration of impact.

In addition to Q1 and Q2 above, this chapter allows for these additional questions:

Q3. For how long do gully features impact downstream biogeochemical structure and function?

Q4. How do streams of differing geomorphic type respond to the influence of gully thermokarst?

Chapter 4. The role of watershed characteristics, permafrost thaw, and wildfire on dissolved organic carbon biodegradability and water chemistry in arctic headwater streams.

Q1: Does BDOC and water chemistry differ at the watershed scale among landscape types?

Q2: Does BDOC and water chemistry differ in streams impacted by thermokarst and fire?

To answer these questions we measured the quantity, biodegradability, and aromaticity of DOC and background water chemistry from arctic headwater streams and rivers. We sampled watersheds in three geographic regions affected by a combination of fire and thermokarst to evaluate controls on DOC quantity and biodegradability at the watershed scale. We hypothesized thermokarst would increase DOC concentrations and BDOC due to the delivery of labile carbon from thawed permafrost. Because wildfire in the Arctic can directly impact DOC export, as well as have secondary effects due to changes in active layer depth and extent of permafrost, we hypothesized that wildfire may decrease BDOC due to the combustion of soil carbon stocks during fire. However, if wildfire promotes extensive permafrost degradation and thermokarst production then BDOC concentrations might increase.

Appendix A. A spatial survey of thermokarst features in the Noatak National Preserve, Alaska and their impacts on arctic stream biogeochemistry

This section reports the findings of a campaign in one of the most remote regions of Arctic Alaska to study the impact of thermokarst on aquatic ecosystems on a regional scale, across various feature type and activity level. We employed the upstream –

downstream approach to sample water quality and (in some cases) functional attributes of impacted rivers and streams.

1.5 Authorship

The work represented in this dissertation is the result of collaboration. The following individuals contributed in the capacity listed below by chapter:

Chapter 2. Impacts of a thermo-erosional gully on ecosystem structure and function of an arctic alluvial tundra stream, North Slope, AK. (Submitted to *Journal of Geophysical Research Biogeosciences* as of 9 September 2014)

Julia R. Larouche¹; William B. Bowden¹; Michael B. Flinn²; Jeff Kampman²

Larouche collected and analyzed samples and performed the data analysis and prepared the manuscript. Kampman provided the macroinvertebrate and sedimentation rate data from his master's work (Kampman 2012). Bowden and Flinn advised on the design of the experiment, assisted with the data analysis, and edited the final manuscript.

Chapter 3. Impacts of a thermo-erosional gully on ecosystem structure and function of an arctic beaded tundra stream, North Slope, AK. (In preparation for peer-review)

Julia R. Larouche¹; William B. Bowden¹; Michael B. Flinn²

Larouche collected and analyzed samples and performed the data analysis and prepared the manuscript. Bowden and Flinn advised on the design of the experiment, assisted with the data analysis, and edited the final manuscript.

Chapter 4. The role of watershed characteristics, permafrost thaw, and wildfire on dissolved organic carbon biodegradability and water chemistry in Arctic headwater streams. (Submitted to *Biogeosciences* as of 24 January 2015)

Julia R. Larouche¹; Benjamin W. Abbott³; William B. Bowden¹; Jeremy B. Jones⁴

Larouche and Abbott designed the experiment, collected and analyzed samples and collaborated closely on the manuscript written by Larouche. Bowden and Jones advised on the design of the experiment, assisted with the data analysis, and edited the final manuscript.

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I am also co-author on two manuscripts led by my colleague, Benjamin W. Abbott.

- Abbott, B. W., Larouche, J. R., Jones, J. B., Bowden, W. B., and Balser, A. W. Elevated dissolved organic carbon biodegradability from thawing and collapsing permafrost. *Journal of Geophysical Research: Biogeosciences*, Volume 119 Issue 10, pp 2049-2063, 2014.
- Abbott, B. W., Jones, J. B., Godsey, S. E., Larouche, J. R., and Bowden, W. B. J. Patterns and persistence of hydrologic carbon and nutrient export from collapsing upland permafrost. *Biogeosciences* (In Review).

**CHAPTER 2. IMPACTS OF A THERMO-EROSIONAL GULLY ON
ECOSYSTEM STRUCTURE AND FUNCTION OF AN ARCTIC ALLUVIAL
TUNDRA STREAM, NORTH SLOPE, ALASKA**

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Title: Impacts of a thermo-erosional gully on ecosystem structure and function of an
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Key Points

- Thermo-erosional gully disturbance led to modest sediment and dissolved solute loading to receiving stream
- Disturbance altered aspects of ecosystem structure and function
- Arctic stream ecosystems are resilient to the disturbance of thermo-erosional gullies

Abstract

The biogeochemical characteristics of a tundra stream on the North Slope, Alaska were quantified over three summer seasons (2009-2011) in response to a gully thermokarst feature that formed in 2005. The results indicate that the permafrost disturbance led to modest loading of sediment and dissolved solutes. We found evidence of altered ecosystem structure (benthic standing stocks, algal biomass, and macroinvertebrate composition) and function (stream metabolism and nutrient uptake), which may be attributable to the previous years' allochthonous gully inputs. Rates of ecosystem production and respiration and benthic chlorophyll-*a* in the impacted reach were significantly lower during the driest of the three summers, even though minimal differences in sediment loading were detected. Rates of ammonium and soluble reactive phosphorus uptake were consistently lower in the impacted reach. Initial macroinvertebrate richness and diversity was low but increased late in the season (August), possibly due to shifts in epilithic resource pools, in particular, allowing grazers to capitalize on allochthonous organic matter. The observed responses in sediment and nutrient loading four years after gully formation were more subtle than expected, likely due to the stabilization of the feature and the dynamics controlling the hydrologic connectivity between the gully and the stream. Nonetheless, we observed differences in metabolism, nutrient uptake and macroinvertebrate community composition, suggesting that even though the geochemical signal diminished, gully features may have long-lasting impacts on the biological aspects of downstream ecosystem function.

Keywords

arctic tundra streams, thermokarst, thermo-erosional gully, permafrost, whole-stream metabolism, TASC nutrient spiraling

1. Introduction

Thermokarst features are potential sources of allochthonous sediment, organic matter, and dissolved solutes to downslope streams, rivers, and lakes, particularly when recently thawed permafrost and disturbed soils become hydrologically connected to receiving waters [Lewis *et al.*, 2011]. Several recent studies have shown alterations to the sediment loading and geochemical signature of aquatic arctic ecosystems impacted by thermokarst disturbance [Bowden *et al.*, 2008; Dugan *et al.*, 2012; Gooseff *et al.*, 2009; Harms *et al.*, 2014; Kokelj *et al.*, 2009; Kokelj *et al.*, 2005; Kokelj *et al.*, 2013; Lamoureux and Lafrenière, 2009; Lewis *et al.*, 2011; Malone *et al.*, 2013; Mesquita *et al.*, 2010]. However no studies to date have evaluated the impact of thermokarst on benthic composition and ecosystem processes in headwater tundra streams. These streams are an important link between tundra hillslopes and higher order reaches that actively process and transport newly thawed, allochthonous carbon (C), nitrogen (N) and phosphorus (P) [Frey and McClelland, 2009; Kling *et al.*, 1991]

Thermokarst features deliver elevated quantities of inorganic N and P [Bowden *et al.*, 2008] and labile dissolved organic carbon (DOC) [Abbott *et al.*, 2014; Cory *et al.*, 2013; Woods *et al.*, 2011] to receiving streams. Previous research has shown that addition of inorganic P enhances ecosystem productivity and respiration in tundra streams and rivers [Bowden *et al.*, 1994; Harvey *et al.*, 1998; Peterson *et al.*, 1985; Slavik *et al.*,

2004]. Conversely, sediment loading has been shown to restrict light availability and promote scour, thus hampering benthic photosynthesis and respiration [Atkinson *et al.*, 2008; Uehlinger and Naegeli, 1998]. Sediment loading also clogs streambed interstitial spaces, interfering with hyporheic and surface water connectivity and the exchange of nutrients and dissolved oxygen [Kasahara and Hill, 2006; Saenger *et al.*, 2005].

Benthic macroinvertebrates are typically the dominant vector of energy flow in lotic systems, connecting primary production to higher trophic levels [Cummins, 1973; Hynes, 1970; Merritt and Cummins, 2006]. These communities are generally patchy and are sensitive to minor disturbance regimes [Lake, 2000]. Allochthonous sediment has been shown to significantly impact habitat composition, leading to profound effects on the distribution of individual organisms [Gammon, 1970; Lenat *et al.*, 1981; Parker and Hury, 2006]. Shifts in community structure can indicate event severity, given that benthic macroinvertebrate diversity and overall community composition are strongly related to ecosystem function [Carter *et al.*, 2006; Vannote *et al.*, 1980].

Although there are several modes of thermokarst formation in upland tundra we focus here on thermo-erosion gullies that often impact lakes, rivers and streams [Jorgenson and Osterkamp, 2005]. We report the results from a comprehensive 2009-2011 characterization of a tundra stream impacted by a 2005 thermo-erosion gully on the North Slope of Alaska. The primary aim was to quantify the enduring impacts of the gully on key hydrobiogeochemical variables across three summer seasons. We hypothesized that elevated sediment input from the gully thermokarst, whether persistent or short-lived, would offset the stimulatory effects of introduced allochthonous C, N, and P on ecosystem structure and function. We expected to observe diminished quality of

benthic resources (e.g., epilithic CNP ratios and algal biomass); reduced ecosystem production and respiration and nutrient uptake rates; and decreased macroinvertebrate richness and diversity in the impacted stream reach.

2. Materials and Methods

2.1 Site description and experimental design

The study area is located on I-Minus stream on the North Slope of the Brooks Range in Alaska, about six miles due south of Toolik Field Station (TFS) (68°38'N, 149°36'W). I-Minus stream originates approximately 3 km from the study reaches on the east side of the Dalton highway and continues until it flows into I-Minus lake approximately 600 meters downstream. I-Minus, a second-order tundra stream, is a high-gradient, alluvial stream with alternating riffle-pool sequences. I-Minus gully feature is located at 68.543188 latitude; -149.522496 longitude (Fig. 1) and was first observed in 2005, but may have formed a year or two prior to discovery. The Reference study reach is approximately 350 meters in length upstream of the thermokarst confluence and has a mean width of 3.07 ± 0.19 and a mean depth of 0.31 ± 0.04 m with a relatively steep slope (mean slope 4.5 ± 0.4 %). The Impacted study reach is approximately 275 m in length downstream of the thermokarst input and has a mean width and depth of 1.40 ± 0.15 m and 0.41 ± 0.04 m, respectively with a lower gradient (mean slope 3.1 ± 0.2 %) compared to the Reference reach. Two primary monitoring stations were established (Fig. 1; Table 1): one at the Impacted stream reach, downstream of the gully influence (M3) and one at the Reference reach, upstream of the gully (M2). Three hillslope locations (Fig. 1; Table 1) were additionally sampled periodically to characterize the

biogeochemical signature of hillslope waters: gully outflow (T1); water track (T2) inputs; and 3) the water directly impacting the receiving stream (T3).

2.2 Hydrology and sediment dynamics

Stream stage was monitored in the Reference reach for summers 2009-2011 and in the Impacted reach for summers 2010-2011, at 5-minute intervals with HOBO water level loggers (Onset Computer Corporation, Inc., Bourne, MA, USA), barometric pressure-corrected and then converted to 5-minute discharge records using a stage-discharge rating curve constructed each summer from current velocity measurements obtained using a FlowTracker Handheld-Acoustic Doppler Velocimeter (SonTek/YSI, San Diego, CA, USA). We attempted to establish the same stage monitoring location each season. All rating curves were with fit with a power function (all R^2 were > 0.94) based on the HOBO stage and FlowTracker discharge measurements.

Since the Impacted reach was not gauged in 2009, we used the linear relationship between discharge in the Reference and Impacted reaches from 2010 and 2011 to predict flow in the Impacted reach in 2009. On days of solute injection experiments, flow was measured using the salt-dilution gauging technique [Kilpatrick and Cobb, 1985; Wlostowski *et al.*, 2013]. In 2011 we decided to move the stage monitoring location in the Impacted reach ~20 m downstream from its location in 2010 because we suspected our stage recorder was missing water flowing under a gravel bar. However, it proved to be difficult to get a good rating curve at this location during the 2011 season due to persistent low flow. To estimate discharge in this reach we developed a relationship between discharge in the Reference reach determined by standard velocity-area profiling and discharge in the Impacted reach determined by salt dilution gauging. Water

contributed by the gully feature to the Impacted reach at T3 (Fig. 2b) was calculated to be the difference in stream flow between M3 and M2 gauged locations, assuming no hillslope water was lost or gained between T3 and M3 locations.

To determine changes in suspended sediment due to thermokarst input, we measured total suspended sediment (TSS) in the Reference and Impacted reach using standard methods (USGS method I-3765). For each sample, a known volume of stream water was filtered in the field through a pre-dried (105°C) and pre-weighed 47-mm diameter glass fiber filter (GF/F) and re-dried and re-weighed. TSS was calculated as the difference in filter mass before and after filtration divided by the volume filtered (mg L^{-1}). Turbidity sensors (DTS-12 from FTS Environmental, Victoria, BC, Canada) were installed in conjunction with automated ISCO samplers (Teledyne ISCO, Lincoln, NE, USA) to collect 5-minute turbidity measurements in the Reference and Impacted reaches for the 2010 season only.

Sediment rates were sampled via substrate traps adapted from *Hedrick et al.* [2005]. Traps consisted of two parts: a 4" diameter, schedule 40 polyvinyl chloride (PVC) base tube with an inner 3" diameter PVC trap. A 3.75" x 4" PVC coupler was used as the base component with two 0.5" slots drilled on opposite sides of the cylinder as holders for the trap. A 2" x 3" schedule 40 PVC cap was used as the trap, with two 1" steel bolts drilled outward on opposite sides that fit into the outer base slots anchoring the trap into the base. During installation, the base was dug into the stream bottom and all inner substrate material removed, allowing the base to remain flush with the streambed. Material removed from the inner base was run through a 4000 μm sieve (US Standard

Size #5), and all >4000 μm material was placed into the 3" trap and installed into the base piece, flush with the stream bottom to simulate native substrate.

Replicate traps were placed along the Reference (M1-M2) reach and downstream Impacted reach (M3-M4) to assess severity of downstream effects. During sampling, traps were carefully removed and collected material was poured through a 4000 μm sieve, with all <4000 μm material collected in a plastic bag, and all >4000 μm placed back into trap and reset within the base. This method was chosen for its ability to minimize substrate disturbance during initial deployment and allow replicate sampling over time, as only the trap portion was removed to retrieve material during each collection event. Samples were collected during June, July and August in 2010 and 2011. In the lab, each sample was poured through a sieve series (2000 μm , 1000 μm , 250 μm) with all fine material (<250 μm) elutriated in a volumetric bucket. A $\geq 100\text{mL}$ aliquot was taken and filtered onto a 25mm glass fiber filter (0.7 μm pore size). Size classes were partitioned with respect to the Wentworth scale of sediment sizes to infer the dominant fraction of sediment. All separated material was dried (60°C, 24hr), weighed, then ashed (500°C, 2hr) and reweighed to determine total mass and organic content within each sample. Data were normalized for period of trap deployment, and sedimentation rates were extrapolated to $\text{g m}^{-2} \text{d}^{-1}$.

2.3 Hydrochemistry

Water samples for chemical analyses were collected with an ISCO autosampler (daily composite stream samples collected four times per 24 hours at 00:00; 06:00; 12:00; 18:00) at the M2 and M3 stations in 2009 and 2010. Grab water samples were taken opportunistically from hillslope locations (T1, T2, T3) 2009-2011 and stream water grab

samples were taken biweekly from the Reference and Impacted reaches in 2011 since the ISCO samplers were not used in 2011. Seasonal mean values were calculated using daily (2009 and 2010) or biweekly (2011) measurements. All water samples were filtered through pre-combusted (450°C) 25-mm diameter GF/Fs with a nominal pore size of 0.07 μm , with the exception of the water designated for base cation analyses, which were filtered with nylon syringe filters with a pore size of 0.45 μm . Separate samples were taken for each analyte. Samples for soluble reactive ortho-phosphate (SRP or $\text{PO}_4^{3-}\text{-P}$), nitrate ($\text{NO}_3^-\text{-N}$), and ammonium ($\text{NH}_4^+\text{-N}$) were frozen; samples for DOC (dissolved organic carbon), TDN (total dissolved nitrogen), TDP (total dissolved phosphorus); and base cations (calcium, Ca^{2+} ; magnesium, Mg^{2+} ; potassium, K^+ ; and sodium, Na^+); micronutrients and metals (aluminum, Al; iron, Fe; manganese, Mn; boron, B; copper, Cu; zinc, Zn; sulfur, S; strontium, Sr; lead, Pb; nickel, Ni; chromium, Cr; and cadmium, Cd) were acidified with 100 μl 6N hydrochloric acid for every 50-mL of sample; and anions (chloride, Cl^- and sulfate, $\text{SO}_4^{2-}\text{-S}$) and alkalinity samples were refrigerated. Samples were shipped back to the University of Vermont in Burlington, Vermont; the Ecosystems Center in Woods Hole, Massachusetts; or the University of Michigan for analysis within six to nine months. Supplementary Table 1 summarizes the methods and instruments used for water chemistry analyses and detection limits.

2.4 Benthic characterization

Epilithic chlorophyll-*a* (chl-*a*) and epilithic particulate CNP were quantified at four riffle stations along the Reference (M1-M2) and Impacted (M3-M4) reach to provide an integrated, reach-scale average estimate. The method utilized to obtain epilithic chl-*a* and particulate CNP followed the ‘whole-rock’ scrub method [*Peterson et al.*, 1993] and

involved scrubbing the epilithic material with a wire brush from the entire surface, top and bottom, of rocks sufficient to cover the bottom of a dishpan of a known area and then rinsed into a known volume of stream water. One dishpan whole-rock scrub was completed at each of the four riffle stations resulting in four bottled scrubbate samples from each reach. Scrubbate was collected in 250-mL amber bottles to prevent further photosynthetic activity and transported back to TFS or base camp. A known amount of epilithic slurry was filtered onto four 25-mm diameter GF/Fs: two for chl-*a*, one for particulate phosphorus (PP) and the fourth for particulate carbon (PC) and nitrogen (PN) analyses. The duplicate chl-*a* filters were extracted in MgCO₃-buffered 90% acetone in the dark on ice for 18-24 h [Strickland and Parsons, 1968] and total chl-*a* was measured fluorometrically using a Turner Designs 10-AU fluorometer (Turner Designs, Incorporated, Sunnyvale, CA, USA). The PP and PCPN filters were dried overnight at 50°C, stored in petri dishes for particulate CNP analyses. Calculations of mean seasonal epilithic standing stocks (CNP) and chl-*a* are based on four stations per reach sampled approximately six times across each summer period (2009-2011).

2.5 Macroinvertebrates

Benthic macroinvertebrates were collected in riffles along each study reach via Surber sampler (0.09 m², 200µm mesh size) three times in June, July and August 2010 and 2011. Five samples were collected along the Reference (M1-M2) and downstream Impacted (M3-M4) reach per sampling event. Samples were placed in plastic bags and preserved in a 10% formalin solution. During processing, each sample was separated into two size classes (>1000µm, >250µm) referred to as coarse and fine fractions, respectively. Invertebrates were picked from each sample, identified to lowest practical

taxonomic unit, primarily genus, and measured for total length. Biomass was estimated using taxa specific length-mass relationships [Benke *et al.*, 1999]. Remaining material was dried (60°C, 24hr), weighed, then ashed (500°C, 2hr) and reweighed to determine benthic organic matter content in each sample. Macroinvertebrates were assigned to functional groups described in Merritt *et al.* [2008]. Taxa richness and Shannon-Weiner index of diversity were calculated for each sample, and raw data were extrapolated to yield abundance and biomass per square meter of stream bottom.

2.6 Stream metabolism

We quantified the net daily metabolism of the Reference and Impacted reach for each gully site from mid-June through mid-August 2009-2011. Whole-stream metabolism (WSM) estimates were based on an open-channel, single station approach [Bott, 1996; Houser *et al.*, 2005; Marzolf *et al.*, 1994] using continuous records of dissolved oxygen (DO) and temperature at 5-min intervals measured by 600-OMS V2 Multi-parameter Water Quality Sondes (YSI Incorporated, Yellow Springs, OH, USA). One sonde was placed at the bottom of the Reference and Impacted reach and were calibrated every 2 weeks in the field and ensured that the two sondes at each thermokarst site read within 1% of the other.

The WSM analysis followed the common approach of Bott [1996] modified for the Arctic environment (i.e., 24-hr light) following that of Cappelletti [2006] and utilized an R-script written by Bowden for this purpose. In general, the approach calculates WSM metrics in units of (g O₂ m⁻³): GEP is volumetric gross primary production; ER is volumetric ecosystem respiration; and NEP is net ecosystem production. The model distinguishes a nighttime period based on a light threshold of 1% and produces an

interpolated ER baseline. The model solves an optimization of the *Platt and Jassby* [1976] photosynthesis-irradiance equation to model NEP on a daily basis. The Energy Dissipation Model [*Tsivoglou and Wallace, 1972*] equation is used to calculate a reaeration coefficient (k) for each data interval based on velocity, which is derived from a function of discharge. Seasonal means of NEP, CR, and GPP were reported from daily estimates during baseflow conditions only as defined by a mean flow or probability of exceedance of 50% from a combined flow duration curve from all three years ($Q < 143 \text{ L s}^{-1}$).

2.7 Stream nutrient spiraling dynamics

Nutrient spiraling metrics, ambient nutrient uptake (U_{amb}) and ambient nutrient uptake length ($S_{\text{w-amb}}$), were measured by Solute Injection Experiments (SIEs) following the dynamic-Tracer Additions for Spiraling Curve Characterization (dyn-TASCC) methodology developed by [*Covino et al., 2010*]. This particular methodology is a modification to the traditional slug approaches e.g. [*Ruggiero et al., 2006; Tank et al., 2008*]. A solution of conservative tracer (sodium chloride, NaCl) and non-conservative tracer (KH_2PO_4 and NaNO_3 or NH_4Cl) dissolved in stream water is released to the head of the study reach as an instantaneous addition and conductivity is measured at 2-second intervals via a HOBO conductivity data logger (Onset Computer Corporation, Inc., Bourne, MA, USA) and with a handheld conductivity meter (YSI) to visually determine when to collect grab samples across the entire slug profile, or tracer breakthrough curve (BTC), across the full range of chloride and inorganic N and P concentrations. Grab samples were kept in the dark while in the field and filtered immediately upon return to TFS with a pre-combusted 25-mm diameter GF/F or a 25-mm cellulose acetate

membrane sterile syringe filter and frozen immediately. The dyn-TASCC approach calculates a distribution of spiraling metric values as a function of nutrient concentration using a longitudinal uptake rate (k_w), which assumes an exponential decline of nutrient concentration with distance downstream. The details of the method and calculations can be found in *Covino et al.* [2010].

2.8 Statistical analyses

Differences between Reference and Impacted reaches were compared using non-parametric Mann-Whitney Rank Sum tests with JMP statistical software (V10, SAS Institute). We considered a range of p-values to be indicative of a notable trend: $\alpha = 0.001$ as highly significant; $\alpha = 0.05$ as significant; and $\alpha = 0.10$ as marginally significant (see Suppl. Table 3). We used non-metric multidimensional scaling (NMDS) and Analysis of Similarity (ANOSIM), both formalized by *Clarke* [1993] to test for differences in water chemistry based on Bray-Curtis dissimilarities [*Bray and Curtis*, 1957]. We selected the NMDS ordination that had the least amount of stress (goodness of fit) and was easiest to interpret. We tested for differences in rank dissimilarity between *a-priori* defined groups using ANOSIM. We considered a comparison with an R value greater than 0.3 to be ‘ecologically significant’. If a p-value was significant ($p < 0.01$), but was associated with an R value less than 0.3, the comparison was considered not significant.

We used a vector analysis to overlay water chemistry variables to the ordination to help determine which factor was contributing to differences (strength of correlation and direction) in *a-priori* groupings. We did not include vectors with correlation coefficients below 0.3 even if the variable had a significant p-value because they did not

help us interpret the multivariate clusters. DECODA (Database for Ecological Community DATA) version 3 [Minchin, 1990] was used to perform the multivariate analyses (NMDS, ANOSIM, and vector analysis).

Differences in sedimentation rates and macroinvertebrate community parameters were assessed using repeated measures Analysis of Variance (ANOVA). Physical and biological parameters collected during each individual sample dates were analyzed using a one-way ANOVA and subsequent post hoc comparisons using Tukey's least significant difference to assess monthly shifts, using a significance level of $\alpha = 0.05$. Means and standard errors were calculated from replicated samples of sediment and macroinvertebrates in each reach for representative data.

3. Results

3.1 Weather and climate

The weather conditions and hydrological dynamics were different across the three study seasons (Figure 2a and 2b). The summers of 2009 and 2010 were characterized by variable weather patterns with two and five notable precipitation events, respectively. The summer of 2011 was extremely dry with very low stream flow compared to the first two years in the three-year dataset. Cumulative degree days for 2009-2011 were 702, 646, and 660, respectively. Cumulative seasonal (June through August) precipitation for the same years was 169.1, 159.0, and 79.8 mm (Table 2).

3.2 Hydrology and sediment dynamics

Hydrographs during the three study seasons were typical of an arctic runoff regime with fast response times and extended recessions. There were two, five, and zero distinct storm events during 2009, 2010 and 2011 field seasons, respectively (Figure 2b).

Table 2 shows area-normalized hydrologic loading (runoff) in mm and percent for sites M2, M3 and T3 for the three study seasons. The amount and percent runoff was greater in 2009 compared to 2010 despite the comparable rainfall amount. Rainfall events in 2009 and 2010 generated high discharge and elevated concentrations of TSS in both reaches of the I-Minus main channel. The 2009 season had the most robust TSS-Q relationship of the three years following a linear ($y = 0.007x + 0.71$ $R^2 = 0.32$) and a power ($y = 0.48x^{0.58}$ $R^2 = 0.42$) function for the Reference and Impacted reaches, respectively (data not shown). Seasonal mean concentrations of TSS at T3 were significantly higher than M2 in 2009 ($P=0.008$) and 2010 ($P=0.028$) and moderately higher in 2011 ($P=0.098$) (Suppl. Tables 2 and 3). Seasonal mean TSS concentrations in the Impacted reach were significantly greater than Reference reach concentrations in 2009 ($P<0.001$, $n=26$) and 2010 ($P=0.001$ $n=25$), but not in 2011 ($P=0.42$ $n=5$) (Suppl. Tables 2 and 3). Impacted reach absolute TSS loadings (concentration multiplied by discharge) were six times the loading of the Reference reach in 2009, twice the loading in 2010, and nearly identical in 2011 (Table 2).

Seasonal mean daily turbidity measured in 2010 was significantly higher in the Impacted (3.36 ± 0.24 NTU $n=56$) compared to the Reference (2.50 ± 0.23 NTU $n=56$) (Mann Whitney $P=0.003$) (Figure 4 D); however, the five-minute data record shows that the Reference reach frequently exceeded the Impacted reach during peak storm periods (Figure 4b). Daily turbidity in the Impacted reach was on average approximately 1 NTU greater than daily turbidity in the Reference reach across the entire season and was approximately 2 NTU higher during 2 out of the 5 events in 2010. The most striking difference in turbidity between the two reaches was during the July 5-8, 2010 storm

which followed a long period (15 days) of baseflow conditions (Figure 4d). It took the Reference reach one day after storm recession to reach baseflow turbidity conditions, while it took the Impacted reach approximately 12 days to return to baseflow turbidity conditions. The two subsequent storm events (peak days Jul 22 and Jul 30) did not differ in mean daily turbidity between the two reaches, although the Impacted reach's mean turbidity remained elevated compared to the Reference during the days following storm recession. We observed no relationship between daily TSS and mean daily turbidity in the Reference reach and a weak relationship in the Impacted reach ($R^2=0.15$) (data not shown). We observed a strong correlation between mean daily turbidity and mean daily discharge following a power function for both the Reference ($y = 0.54x^{0.36}$ $R^2 = 0.76$) and Impacted ($y = 0.53x^{0.41}$ $R^2 = 0.69$) reaches (data not shown). The Reference mean turbidity above and below the discharge threshold of 10% exceedance (244 L s^{-1} for 2010) was 5.09 NTU and 2.11 NTU, respectively. Impacted mean turbidity above and below the 10% exceedance threshold was 5.64 NTU and 3.02 NTU, respectively. Reference mean turbidity above and below the discharge threshold of 50% exceedance (40 L s^{-1} for 2010) was 3.45 NTU and 1.41 NTU, respectively. Impacted mean turbidity above and below the 10% exceedance threshold was 4.42 NTU and 2.22 NTU, respectively.

Total sedimentation rates ($\text{g m}^{-2} \text{ d}^{-1}$) measured in 2010 and 2011 were significantly higher in the Impacted reach in both years ($P<0.05$). In 2010, the rate measured in the Impacted reach ($177.8 \text{ g m}^{-2} \text{ d}^{-1}$) was an order of magnitude higher compared to the Reference ($79.9 \text{ g m}^{-2} \text{ d}^{-1}$) and the rates measured in 2011 (Reference: 13.8; Impacted: 19.2) were only a fraction of those observed in 2010. The percent organic

matter composition of sediment decreased (2010: from 8.4% to 6.8%, ns; 2011: 21.1% to 15.9%, ns) in the Impacted reach, indicating more inorganic allochthonous sediment introduction from thermokarst inputs.

3.3 Hydrochemistry

The primary sampling stations established for this study allow a comparison of nutrient loading at different scales from undisturbed and disturbed tundra locations. Comparing the main channel and tributary stations (Fig. 1) provides information about how the thermokarst disturbance may or may not impact flowing waters of the tundra on a fairly small scale (< 5 km²). Comparison of T1 vs T2 describes differences between water flowing from the thermokarst and water flowing in a common drainage feature in the tundra. Comparison of T1 vs. T3 - a combined outflow of the thermokarst and water track - shows if there is an effect on the water as it travels down the hillslope from the thermokarst disturbance to the receiving main channel. Comparison of M2 vs. T3 reveals whether the hillslope outflow has a unique signature compared to the upstream main channel. Finally, comparison of M2 vs M3 informs whether there is an immediate impact of the low hillslope tributary (T3) on the downstream main channel.

Supplementary Table 2 reports the numerical values of a suite of hydrochemistry variables for each sampling location and Supplementary Table 3 reports the statistical significance of key comparisons and between sampling locations. Counter to expectation, the specific conductance of the Impacted (M4) reach was lower than that of the Reference (M2) reach, due to a dilution effect of the T3 water having a low specific conductance. Seasonal mean daily specific conductance in the Impacted reach (mean 63.1 ± 1.0 uS cm⁻¹

¹) was significantly lower compared to the Reference (68.0 SE 1.5 μScm^{-1}) in 2010 (Mann Whitney, $P=0.07$).

In general, the outflow of the gully thermokarst (T1) had significantly greater concentrations of DOC, TDN, $\text{NH}_4\text{-N}$, and Fe compared to the adjacent water track (T2) and hillslope outflow (T3). The hillslope outflow (T3) contained significantly higher concentrations of DOC, TDN, Fe, Mn and TSS and significantly lower alkalinity compared to the Reference receiving stream (M2). Despite these differences in chemistry among hillslope locations, the differences in these solutes were not all significant between the Reference (M2) and Impacted (M3) reaches, except for greater Fe and Mn concentrations in M3 in all three years and greater TSS in 2009 and 2010. The only solute that increased as a function of increasing discharge was DOC. There was a strong relationship ($R^2=0.78$, data not shown) between DOC concentration and discharge in both receiving stream reaches across the three study seasons, thus this relationship cannot be attributed to an effect of thermokarst input.

There were small differences in area-specific loadings among biogeochemical variables between the Reference and Impacted reach (Table 2). TSS and $\text{NH}_4\text{-N}$ area-specific loadings were greater in M3 in 2009 and 2010. Impacted reach absolute loadings were typically higher than the Reference reach, primarily due to greater discharge. Rainfall in 2009 and 2010 produced elevated discharge and therefore the flux of all solutes in both reaches. The solutes that were consistently greater in cumulative flux in the Impacted reach compared to the Reference were TSS, DOC and TDN (Table 2).

The Reference and Impacted reaches were not significantly different in water chemistry (Fig. 3; ANOSIM Global $R = 0.15$ $P = 0.000$, Suppl. Table 4) despite the

hillslope locations (T1, T2, and T3) having significantly different biogeochemical signatures when each are compared to M2 and M3 (Fig. 3; ANOSIM Global R values ranges from 0.80 to 0.93; Suppl. Table 4). The T1 (thermokarst) centroid is larger and more varied compared to the T2 (water track) and T3 (combined thermokarst and water track) centroids. As expected, the T3 centroid overlaps both T1 and T2. The water chemistry of the thermokarst outflow (T1) is significantly different compared to the adjacent water track (T2) (ANOSIM $R = 0.35$ $P=0.000$; Suppl. Table 4). The comparison between T1 versus T3 and T2 versus T3 are not different (ANOSIM $R = 0.30$ and $R = 0.26$, respectively, Suppl. Table 4), and expected given that T3 is a combination of both T1 and T2 water.

The vector analysis (arrows overlain on Fig. 3) shows which variables are potentially driving differences in water chemistry across locations. The variables included in the vector analysis and their respective correlations with the two dimensions of the NMS solution and significance are reported in Suppl. Table 5. The thermokarst outflow (T1) tended to contain higher concentrations of DOC, TDN, NH_4^+ , Fe^+ and Mn^+ compared to its adjacent reference water track (T2) (Mann-Whitney comparisons, Suppl. Table 3). Likewise, the receiving main channel tended to contain higher concentrations of Cl^- , Ca^+ , Na^+ , Mg^+ , S, NO_3^- , SO_4^- , and alkalinity.

3.4 Epilithic chlorophyll-a and CNP standing stocks

Epilithic chl-*a*, a measure of autotrophic biomass, was significantly higher in the Impacted reach in 2009 (t-test $P<0.05$), not significantly different in 2010 ($P=0.26$) and significantly lower than the Reference reach in 2011 ($P<0.05$) (Table 3). Standing stocks of carbon were significantly greater ($P<0.05$) in the Impacted reach in all three seasons

and nitrogen was significantly greater in 2009 and 2010 ($P < 0.05$). Differences in phosphorus standing stocks were detected in 2011 only ($P = 0.002$). Epilithic molar ratios (C:N, C:P, N:P), an indication of basal resource quality, had a tendency to be significantly higher in the Impacted reach across all three seasons.

3.4 Macroinvertebrate communities

Macroinvertebrate assemblages in I-Minus were primarily dominated by insect larvae, though high abundances of oligochaetes were not uncommon. There was a high diversity of functional groups present: *Baetis* sp., *Acentrella* sp. (Baetidae; mayfly), *Cinygmula* sp. (Heptageniidae; mayfly), and *Orthocladius* sp. (Chironomidae; midge) were the dominant grazers, *Nemoura* sp., *Podmosta* sp. (Nemouridae; stonefly) and *Tipula* sp. (Tipulidae; crane fly) represent the shredder community, though were far less abundant. Several dipteran collector-gatherers were present, with few predatory taxa including *Procladius* sp. and *Ablabesmyia* sp. (Chironomidae; midge). Filter-feeding *Gymnopsis* sp. and *Prosimulium* sp. (Simuliidae; black fly) were also abundant [Kampman, 2012].

In general, early in the 2010 and 2011 seasons we observed increased abundance and decreased diversity of macroinvertebrate composition in the Impacted reach and observed the opposite trend later in the seasons (Table 5). June samples (both years) indicated an increased in overall community abundance and biomass in the Impacted reach, although not significant (NS). Diversity and taxa richness measured in June 2010 was marginally lower compared with the Reference reach (ANOVA $P < 0.1$). By July 2010, the June trend had reversed and community abundance ($P = 0.03$) and biomass ($P = 0.08$) were significantly lower in the Impacted reach relative to the Reference (NS in

August 2010). Community diversity and taxa richness also trended higher during these sample periods, but NS. In 2011, macroinvertebrate data revealed similar trends as those observed in 2010. June samples trended upward in abundance in the Impacted reach; however, biomass was noticeably lower compared with the Reference reach (NS). Diversity was significantly lower compared with the Reference reach in June 2011 ($P=0.06$) and July ($P=0.02$). Overall abundance was marginally lower in the Impacted ($P=0.08$) reach in July and the trend became stronger and highly significant ($P=0.003$) in the August sampling. Biomass was significantly lower in the Impacted reach during August 2011 ($P=0.08$). No significant differences were found in taxa richness in any of the months in 2011.

There were primarily differences in scraper/grazer taxa between Reference and Impacted reaches in 2010 and 2011 (data not shown). No significant shift of dominant taxa in the Impacted reach was observed in June 2010. As the season progressed, samples from July and August revealed a significant decrease in scraper/grazer ($P<0.001$) and a downward trend (NS) in collector-gather communities driven primarily by losses in the baetid mayfly *Acentrella* sp., and chironomids *Orthocladius* sp. and *Corynoneura* sp., respectively. Similar to 2010, no significant shift of dominant taxa occurred in June 2011. As the season progressed there was a significant decrease in the scrapers *Acentrella* sp. and *Cinygmula* sp in July ($P<0.05$) and August ($P<0.001$) 2011. There was no significant difference in coarse ($>1000\mu\text{m}$) or fine ($>250\mu\text{m}$) benthic organic matter between Reference and Impacted reaches during 2010 or 2011, and coarse benthic organic matter was the dominant size fraction collected in each sample during both seasons (data not shown).

3.5 Whole-stream metabolism

Seasonal mean rates of gross ecosystem production (GEP), ecosystem respiration (ER), and net ecosystem metabolism (NEM) differed significantly ($P < 0.001$) between the Reference and Impacted reaches in the 2011 season only (Fig. 5). Seasonal mean rates of GEP for 2009, 2010 and 2011 in the Reference reach ranged from: 0.24 to 1.97, 0.43 to 2.14, and 0.19 to 2.81 $\text{g m}^{-2} \text{d}^{-1}$., respectively. Impacted reach rates of GEP for 2009-2011 ranged from: 0.24 to 2.57; 0.50 to 3.34; and 0.00 to 1.70 $\text{g m}^{-2} \text{d}^{-1}$. Reference mean rates of ER ranged from: -0.86 to -13.75; -0.07 to -15.14; and -1.18 to -9.07 $\text{g m}^{-2} \text{d}^{-1}$, while Impacted mean ER rates ranged from -0.50 to -23.90; -0.12 to -14.93; and -0.26 to -9.77 $\text{g m}^{-2} \text{d}^{-1}$. There is a strong linear correlation between the predicted rates of NEM based on the optimization model of the Jassby-Platt photosynthesis-irradiance equation to the observed WSM field DO data, indicating that the model fits the data appropriately (data not shown). The seasonal mean GEP/ER ratios across 2009-2011 for the Reference reach were -0.30, -1.60, and -0.23, respectively, while the Impacted mean GEP/ER ratios were -0.33, -1.49, and -0.14. Multiple linear regression analysis did not yield any significant relationships between metabolic estimates and potential explanatory variables (e.g., light, stream temperature, discharge, inorganic nutrients, DOC, TSS, turbidity) (data not shown).

3.6 Nutrient spiraling

Solute injection experiments (SIEs) were conducted during similar discharge conditions, four times during June and August 2010 and 2011. No measurable uptake of

NO_3^- was observed in any reach at any time (Table 4). Ambient nutrient concentration and ambient uptake rates (U_{amb}) of NH_4^+ and PO_4^{3-} were generally greater in the Reference reach (Table 4). Exceptions included no measurable uptake in both reaches in June 2010 and higher uptake measured in the Impacted reach in August 2010 for PO_4^{3-} alone. Nitrate concentrations were 1.5 times higher in the Reference compared to the Impacted reach on two of the four SIE dates. On average, NH_4^+ and PO_4^{3-} ambient concentrations were nearly double in the Reference reach compared to the Impacted reach. Ammonium uptake rates were 5 times higher in the Reference compared to Impacted over the 3 SIEs where uptake was observed. Phosphate uptake rates were 1.5 times greater in the Reference reach during 3 of the SIEs. Ammonium uptake lengths were on average 4.4 times longer in the Impacted reach on all SIEs. Phosphate uptake lengths were on average 6 times longer in the Impacted reach during 3 of the SIEs. We observed corresponding WSM and nutrient uptake patterns on SIE dates (i.e., higher rates in the Reference reach compared to the Impacted).

4. Discussion

4.1 Comparison of sediment dynamics between Reference and Impacted reaches

In recent studies of Arctic aquatic systems, researchers concluded that thermo-erosional activity had contrasting impacts on sediment loading to downslope ecosystems. Conclusions with respect to sediment loading following permafrost disturbance ranged from substantial and persistent [Bowden *et al.*, 2008; Calhoun, 2012] to short-lived or minimal [Dugan *et al.*, 2012]. We found that modest sediment loading can persist even years after initiation; however, the increase in sediment and turbidity were largely dependent on the degree of storm activity to mobilize and connect hillslope sediment

from the gully to the stream. We also found that despite the fine size of the mobilized sediment, the majority was deposited in the upper portion of the Impacted reach, with subsequent storm events resuspending and transporting previously deposited sediment. Field observations suggest that thermokarst sediment input decreased considerably across 2009-2011, due to a combination of the gully feature recovering between sampling seasons and low storm activity in 2011; however, the Impacted reach stream bed was still noticeably influenced from previous years' sediment introduction as substrate interstitial space remained inundated with fines.

We observed elevated turbidity in the Impacted reach during baseflow conditions and during storm events. We expected the turbidity in the Impacted reach to be substantially greater than in the Reference reach. At I-Minus, the sediment mobilized from the thermo-erosional feature is diluted by runoff from the surrounding, unimpacted tundra (T2) and a substantial portion is deposited in the water track on the way to the mainstem of the stream, with resuspension during large storm events likely. We observed high turbidity values in the Impacted reach during storm events and for many days following when preceded by long periods of dry, baseflow conditions (Fig. 4). The thermokarst gully contributed sediment to the receiving stream reach, but the magnitude of the impact was dependent on the activity level of the feature and its connectivity downslope, as well as the storm activity of the season.

4.2 Comparison of water chemistry between Reference and Impacted Reaches

In general, the vector analysis indicates which variables account for the differences between main channel and hillslope water chemistry. The hillslope waters and main channel have distinct water chemistry and despite the input of water at T3 having a

different signature, the reference and impacted reaches remain similar. This may be due to the effect of dilution or the fact that T1 and T2 waters combine and flow down the hillslope through a swath of vegetation acting as a filtration bed. Field observations note that the T3 sampling location began to resemble that of a stream bed by the end of the study, meaning that outflow from hillslope gully thermokarst may lead to gradual channel formation.

The loading of dissolved nutrients to the Impacted reach was much lower than we expected. Similar to other studies [*Bowden et al.*, 2008; *Frey and McClelland*, 2009; *Harms et al.*, 2014; *Kokelj et al.*, 2009; *Kokelj et al.*, 2005; *Kokelj et al.*, 2013] the gully outflow (T1) contained high concentrations of some key macro- and micronutrients (DOC, TDN, TDP, NH_4^+ , and Fe) detected at T1 (Supplementary Table 1). However, the area-specific loading of these nutrients were approximately 10x lower in the hillslope outflow (T3) compared to the receiving stream locations (M2 and M3). Therefore, the signature of the gully outflow (T1), although containing high concentrations of solutes, did not have a substantial impact on receiving stream concentrations. This observation may be explained by the water track that coincides with the gully outflow creating a dilution effect, thus buffering the impact of T1 outflow entering the receiving stream at M3. Moreover, the wet sedge area between T1 and T3 may sequester nutrients and trap sediment. Interestingly, alkalinity concentrations were lowest and at T1 and T2 and higher at T3 compared to T1, yet alkalinity was greatest overall in the mainstem channel (M2 and M3). This is likely due to the release of weathered constituents with active layer thaw and interaction as the water moves down the hillslope [*Hobbie et al.*, 1999].

Alkalinity in the stream increased over the thaw season (data not shown), likely due to increase in the stream channel thaw bulb and greater interaction with the hyporheic zone.

Deeper thermokarst features such as retrogressive thaw slumps are becoming more common, particularly during anomalous seasonality conditions [Balsler *et al.*, 2014] and tend to have a more discernible impact on aquatic chemistry [Calhoun, 2012; Kokelj *et al.*, 2009; Kokelj *et al.*, 2013; Malone *et al.*, 2013] compared to shallow active layer disturbances (e.g active layer detachments and gullies). Malone *et al.* [2013] concluded that sulfate (SO_4^-) dissolution is the main process responsible for the geochemical composition of impacted streams, yet we found that our Reference reach SO_4^- concentrations at M2 are higher than those at T3. Lewis *et al.* [2011] found inorganic solute yields from late summer rainfall are higher because the thick active layer maximizes hydrologic interactions with mineral soils and generates high solute concentrations because rainfall hydrologically connects areas otherwise isolated.

4.3 Comparison of ecosystem structure between Reference and Impacted reaches

We observed no consistent trend in epilithic chl-*a* between the two reaches. On average, standing stocks of C and N were nearly two times higher in the Impacted reach compared to the Reference reach in 2009 and 2010. Consequently, the ratios of C:N and C:P were greater in the Impacted reach, indicative of a lower quality epilithic resource, likely due to hillslope material entering the stream during the more active seasons immediately following gully initiation.

Macroinvertebrate community data collected during 2010 and 2011 supports the hypothesis that late season scraper/grazer communities are significantly lower in Impacted reaches as collector abundance increased, potentially due to amplified

sedimentation. Many studies have shown that elevated levels of fine sediment in lotic systems can reduce habitat and food quality [Henley *et al.*, 2000; Wood and Armitage, 1997]. Lemly [1982] showed that a heavy accumulation of fines can have significant physical impacts on macroinvertebrates, affecting gill structures that may impede diffusion of oxygen and cause respiratory stress. Accumulation of inorganic fines may also affect feeding ability by physically impairing the mouth parts of these organisms [Gammon, 1970] with grazer taxa collected in 2010 in the Impacted reach demonstrating such physical impairment.

We predicted that taxa richness and diversity would be significantly lower in reaches downstream of thermokarst inputs. Our data suggests the impacts of the gully thermokarst were more complex. The initial decreases in richness and diversity in the Impacted reach were mitigated later in the season as shown by higher richness and diversity in late July and August. This finding suggests that resource pools can shift during the active season, and though biofilm quality decreases, new niches are created by increased allochthonous organic matter that can potentially be utilized by collector taxa.

4.4 Comparison of ecosystem function between the Reference and Impacted reaches

We hypothesized that the negative effects of sediment deposition would overwhelm the stimulatory effects of nutrient loading. We also expected lower nutrient uptake rates and longer uptake lengths in the Impacted reach. Despite the minimal contribution of solutes observed in the receiving stream during the study, we observed some differences in whole-stream metabolism and nutrient uptake. This is one of few studies that assessed the impact of thermokarst on stream metabolism [Calhoun, 2012] and the only study to date that has evaluated the impact of thermo-erosional loading on

nutrient dynamics. *Calhoun* found that turbidity increased by several orders of magnitude below a massive thaw slump that impacted the Selawik River in northwest Alaska and in response, daily rates of GPP and ER decreased by 63% and 68%, respectively, in the downstream reach. However, the direct loading of sediment to the Selawik River was many orders of magnitude greater than we observed in our study of the headwater I-Minus stream.

The functional variables measured support our hypothesis that metabolism and nutrient uptake were lower in the Impacted reach due to sediment loading. We observed significant differences in metabolism metrics for 2011 only – the dry year when we did not detect any differences in sediment or nutrient concentrations. Productivity, respiration and chl-*a* were all greater in the Reference reach in 2011. The nutrient spiraling experiments in 2010 and 2011 suggest higher nutrient uptake and shorter uptake length in the Reference reach.

There is a “cause and effect” conundrum in this study in that the Reference reach was slightly steeper and wider than the Impacted reach. It was not clear if the presence of the gully thermokarst was caused by this geomorphic difference or whether previous, long-term (decade to century) thermos-erosional activity at this site created the geomorphic difference between the reaches. This of course has a direct bearing on how to interpret the differences we observed in hydrogeochemical and ecological characteristics of the two reaches. *Lewis et al.* [2011] and *Dugan et al.* [2009] concluded that other factors (i.e., active layer development due to a greater proportion of south-facing slopes; antecedent soil moisture and temperature conditions) rather than the presence of active layer detachment slides, explained higher dissolved solute fluxes in watersheds in

northern Canada. It is also possible that our observations were the result of legacy effects on stream function from years of much higher sediment loading following the initial feature formation.

4.5 Landscape perspective and resilience

The disturbed gully area is approximately 1,500 km², making up 1% of the T1 sub-watershed, 0.15% of the T3 sub-watershed, and a mere 0.03% of the M3 (Impacted) watershed. Gully thermokarsts are the most common type of thermo-erosional features on the landscape in the region around Toolik Lake, comprising 53% of the thermokarst accounted for in a 1,681 km² area [*Krieger, 2012*] and remain active for approximately 3-10 years [*Godin and Fortier, 2012; Lewkowicz and Harris, 2005*]. Given this perspective, the integrated, landscape-scale hydrobiogeochemical effect of spatially isolated gully thermokarst may be small. Geochemical impacts of large retrogressive thaw slumps have been detected at the 10² -10³ km² watershed scale [*Kokelj et al., 2013*]. However, at the larger regional scale it remains unclear whether either large numbers of small thermo-erosional features or small numbers of large thermo-erosional features have significant, long-term effects on stream and river ecosystem structure and function in the Arctic.

It is possible that arctic stream ecosystems are more resilient to the disturbance of thermo-erosional gullies than previously expected. Thermo-erosional features tend to become less active and begin to revegetated within a few years to several decades (Pizano et al., in review) [*Godin and Fortier, 2012; Lewkowicz and Harris, 2005*], though some lake-side glacial thaw slumps may remain active much longer. This study was conducted approximately four to seven years after the initial disturbance. It is likely that differences in nutrient and sediment loadings between the two reaches were greater in the first few

years following the initial disturbance as seen in a nearby gully feature on the Toolik River [Bowden *et al.*, 2008].

Furthermore, hydrologic connectivity (i.e., distance between feature and downslope aquatic ecosystem as well as the presence and position of drainage water tracks) likely plays an important role on the magnitude of impact. At our study site, the distance (< 1 km) between the thermokarst feature and the receiving stream, particularly during dry years, reduced solute loading to the stream through a combination of dilution, removal, and processing. Others [Lafrenière and Lamoureux, 2013; Lamoureux and Lafrenière, 2009; Lewis *et al.*, 2011] also have a difficult time ascribing differences in watershed biogeochemistry to thermokarst disturbances alone. Additional factors such as random inter-annual variability, seasonality and topography and relative connectivity of feature to stream may play a role in explaining observed differences.

5. Conclusions and Implications

We conclude that: 1) Although the direct outflow from a gully thermokarst can contain high concentrations of sediment and dissolved constituents, the likelihood of observing an impact in the downslope stream depends on ‘hydrological connectivity’ (i.e., storm activity, presence of water tracks, distance between stream and feature). 2) Despite subtle impacts on the geochemistry of the Impacted stream, an examination of functional attributes (e.g., whole-stream metabolism, nutrient spiraling, macroinvertebrate community composition) revealed significant differences at a local scale, which may be due to previous as well as current solute and sediment loading. 3) At some impacted stream sites (such as I-Minus), it might be difficult to separate the effect of the gully thermokarst from the effect of other environmental characteristics, such as

the geomorphic form of the receiving stream. 4) Gully thermokarst may not be sufficiently large or numerous to significantly affect stream ecosystem function at a regional scale. 5) Gully thermokarst features may stabilize sufficiently quickly that – by themselves – they do not significantly affect stream ecosystem structure or function at a regional scale.

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Table 1

Sampling location descriptions, GPS coordinates, and contributing watershed areas of the I-Minus hillslope tributary and main stem locations of receiving stream

ID	Description	Latitude (DD)	Longitude (DD)	Watershed area (km ²)
M1	Reference reach, upper	68.546520	-149.514621	4.09
M2	Reference reach, just above TK confluence	68.548063	-149.521309	4.35
M3	Impacted reach, just below TK confluence	68.548205	-149.521747	5.37
M4	Impacted reach, lower	68.549885	-149.525409	5.77
T1	Outflow from TK gully feature	68.544115	-149.522384	0.15
T2	Hillslope water track, adjacent to TK outflow	68.544378	-149.521467	0.76
T3	TK water track low, before entering stream	68.547864	-149.521309	1.00

Table 2

Summary of area-specific and absolute cumulative water and solute mass flux for 3 sampling locations at I-minus2 (2009-2011). Sample sizes for solutes 2009-2011 are 58, 63, and 61 days, respectively. Flux estimates from sampling points (T1) and (T2) are not reported due to lack of reliable flow data from the hillslope locations. Runoff calculations based on daily mean discharge from 5-minute data. Precipitation and Runoff units are mm; all other metrics are kg km⁻² for area-normalized and absolute loading (kg)

Year/Metric	Area-normalized Loading (kg km ⁻²)			Absolute Loading (kg)		
	M2	M3	T3	M2	M3	T3
2009						
Precipitation				169.1		
Runoff	78.5	74.0	56.0			
Runoff %	46.4	43.8	33.1			
DOC	592	567	66.8	2575	3045	66.8
TDP	0.29	0.32	0.05	1.26	1.72	0.05
SRP	0.18	0.19	0.01	0.78	1.02	0.01
DON	17.0	16.1	1.7	74.0	86.4	1.69
TDN	17.7	16.4	1.8	77.0	88.1	1.80
NH ₄	1.33	1.52	0.14	5.79	8.16	0.14
NO ₃		nd			nd	
TSS	90.6	438.1	2173	394	2352	2173
2010						
Precipitation				159.0		
Runoff	125.2	122.2	111.7			
Runoff %	78.5	76.7	70.1			
DOC	1186	1238	113	5159	6648	113
TDP	0.66	0.53	0.06	2.87	2.85	0.06
SRP	0.65	0.61	0.04	2.83	3.28	0.04
DON	29.6	30.3	3.57	128.8	162.7	3.57
TDN	34.6	34.1	3.7	150.5	183.1	3.70
NH ₄	1.67	3.05	0.14	7.26	6.39	0.14
NO ₃	1.23	0.96	0.04	5.35	5.16	0.04
TSS	110.2	182.1	552.0	479.4	977.9	552.0
2011						
Precipitation				79.8		
Runoff	22.1	17.2	9.3			
Runoff %	27.7	21.5	11.7			
DOC	130	120	10.13	565.5	644.4	10.13
TDP	0.11	0.05	0.004	0.48	0.27	0.004
SRP	0.06	0.04	0.01	0.26	0.21	0.01
DON	4.19	3.49	0.35	18.2	18.7	0.35
TDN	4.93	4.16	0.38	21.5	22.3	0.38
NH ₄	0.43	0.31	0.03	1.87	1.66	0.03
NO ₃	0.41	0.35	0.002	1.78	1.88	0.002
TSS	11.3	10.1	21.1	49.2	54.2	21.1

Table 3

Epilithic chlorophyll-a, standing stocks and molar ratios of epilithic carbon, nitrogen and phosphorus from rocks in the Reference and thermokarst-Impacted reach. Seasonal mean, sample size (n = days), and 1 standard error (SE) are reported. The significance of differences between stream samples taken along the Reference (M1-M2) and Impacted (M3-M4) were tested with a t-test and values in bold with ^a following the mean indicate significantly higher means at the $\alpha = 0.05$ level

	2009		2010		2011	
	Reference	Impacted	Reference	Impacted	Reference	Impacted
Chlorophyll-a ($\mu\text{g}/\text{cm}^2$)						
mean	0.20	0.33^a	0.29	0.37	0.53^a	0.38
SE	0.03	0.04	0.05	0.05	0.07	0.04
n	15	15	16	16	20	20
Standing Stocks ($\mu\text{mol}/\text{cm}^2$)						
Carbon						
mean	11.1	25.3^a	16.6	27.7^a	32.0	39.0^a
SE	0.6	1.7	2.7	3.9	2.9	3.3
n	15	15	16	16	20	20
Nitrogen						
mean	0.97	1.80^a	1.69	2.77^a	3.01	2.73
SE	0.06	0.12	0.27	0.43	0.34	0.29
n	15	15	16	16	18	20
Phosphorus						
mean	0.05	0.07^a	0.07	0.06	0.08	0.05
SE	0.01	0.01	0.01	0.01	0.01	0.01
n	15	15	16	16	20	20
Molar Ratios						
C:N						
mean	11.6	14.1^a	10.2	12.2^a	11.0	14.3^a
SE	0.4	0.3	0.3	1.2	0.3	0.4
n	15	15	16	16	18	20
C:P						
mean	263	348^a	229	527^a	744	853
SE	30	23	16	55	311	64
n	15	15	16	16	20	20
N:P						
mean	22.7	24.8	23.1	79.0^a	70.5	59.8
SE	2.5	1.8	1.9	27.6	30.1	4.9
n	15	15	16	16	18	20

Table 4

Nutrient spiraling and associated whole-stream metabolism (WSM) metrics for solute injection experiment (SIE) dates in June and August 2010 and 2011 at I-Minus Reference (M1-M2) and thermokarst-Impacted (M3-M4) reaches

	6/24/2010		8/14/2010		6/25/2011	6/23/2011	8/11/2011	8/9/2011
	Reference	Impacted	Reference	Impacted	Reference	Impacted	Reference	Impacted
Daily Mean Q (L s ⁻¹)	13.5	23.1	86.9	93.5	40.5	22.2	6.6	8.2
<i>Nutrient Spiraling Metrics</i>								
NO₃-N								
S _{w-amb} (m)	-	-	-	-	-	-	-	-
U _{amb} (μg m ⁻² min ⁻¹)	no uptake	no uptake	no uptake	no uptake	no uptake	no uptake	no uptake	no uptake
NO ₃ -N _{amb} (μg L ⁻¹)	8.3	5.0	0.8	1.1	12.1	12.5	40.0	26.5
NH₄-N								
S _{w-amb} (m)	-	-	435	1949	1054	2180	203	1355
U _{amb} (μg m ⁻² min ⁻¹)	no uptake	no uptake	17.6	2.2	10.3	2.8	21.5	3.7
NH ₄ -N _{amb} (μg L ⁻¹)	1.4	17.6	5.0	1.4	19.6	9.9	18.2	10.4
PO₄-P								
S _{w-amb} (m)	-	-	419	273	48.0	469	95.0	225
U _{amb} (μg m ⁻² min ⁻¹)	no uptake	no uptake	17.6	69.5	83.2	4.8	19.6	14.7
PO ₄ -P _{amb} (μg L ⁻¹)	7.1	2.1	4.8	6.2	7.2	3.6	7.7	6.9
<i>WSM Metrics</i>								
GEP (g O ₂ m ⁻² day ⁻¹)	3.7	2.3	no data		3.7	1.4	1.5	0.1
CR (g O ₂ m ⁻² day ⁻¹)	-0.3	-1.0	no data		-23.5	-7.3	-7.9	-1.9
NEP (g O ₂ m ⁻² day ⁻¹)	3.4	2.3	no data		-19.7	-5.9	-6.4	-1.7

Table 5

Benthic macroinvertebrate parameters measured in I-Minus receiving stream in 2010 and 2011. Monthly means \pm 1 standard error (SE) are reported of 5 samples collected per reach (n = 10 per month). The significance of differences between stream samples taken along the Reference (M1-M2) and Impacted (M3-M4) were tested with an ANOVA and values in bold with ^a following the mean indicate significantly higher means at the $\alpha = 0.05$ level

	June 2010		July 2010		August 2010		June 2011		July 2011		August 2011	
	REF	IMP	REF	IMP	REF	IMP	REF	IMP	REF	IMP	REF	IMP
Total Abundance (# organisms m ⁻²)												
mean	1070	1865	2700^a	1126	764	520	899	1097	1248	701	1008^a	499
SE	196	437	534	261	271	97	141	607	230	144	102	61
Total Biomass (g m ⁻²)												
mean	149	275	559	243	223	133	357	139	409	478	1112	372
SE	63	54	109	118	58	37	128	59	73	173	349	126
Taxa Richness (# of taxa)												
mean	7.6	6.0	11.8	11.2	4.4	6.0	7.4	6.2	10.0	9.0	7.2	7.8
SE	0.2	0.7	0.7	1.2	0.2	0.9	0.6	1.0	0.4	0.5	0.4	0.4
Total Diversity (S-W Index H ²)												
mean	1.4	1.0	1.8	1.6	1.1	1.3	1.5^a	1.1	1.8	1.7	1.5	1.7^a
SE	0.1	0.2	0.1	0.1	0.2	0.1	0.1	0.1	0.1	0.1	0.05	0.05

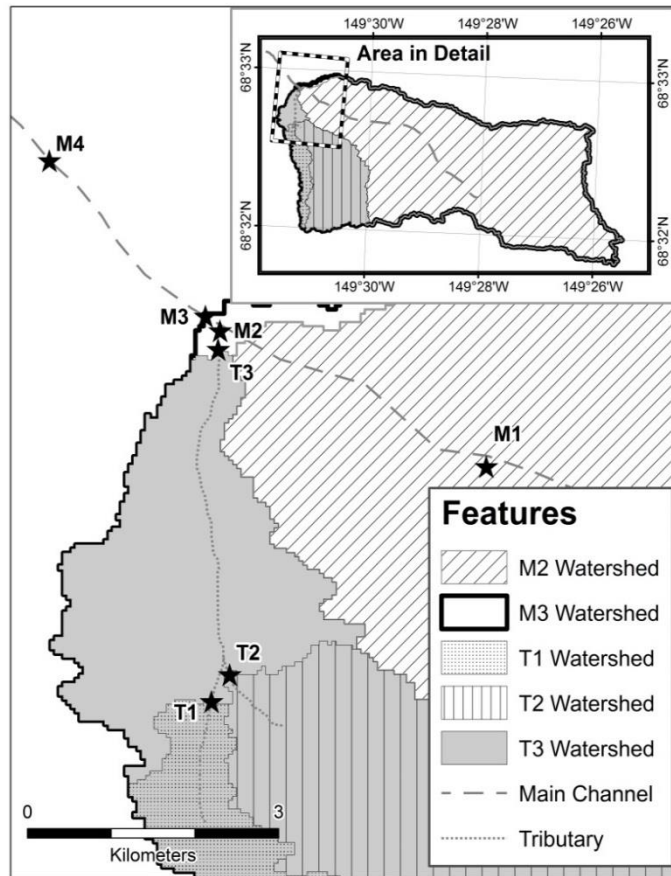


Figure 1. Study area including I-Minus hillslope gully thermokarst (located just south of T1 sampling point) and the I-Minus receiving stream. Primary sampling locations along the I-Minus main stem are: M1 (upper reference reach); M2 (lower reference reach), M3 (upper impacted reach); and M4 (lower impacted reach). Hillslope sampling locations along the gully thermokarst tributary are: T1 (outflow from gully feature); T2 (adjacent water track); and T3 (combined gully and water track outflow before entering main channel). Map credit: R. Fulweber, Toolik Field Station GIS and Remote Sensing Facility.

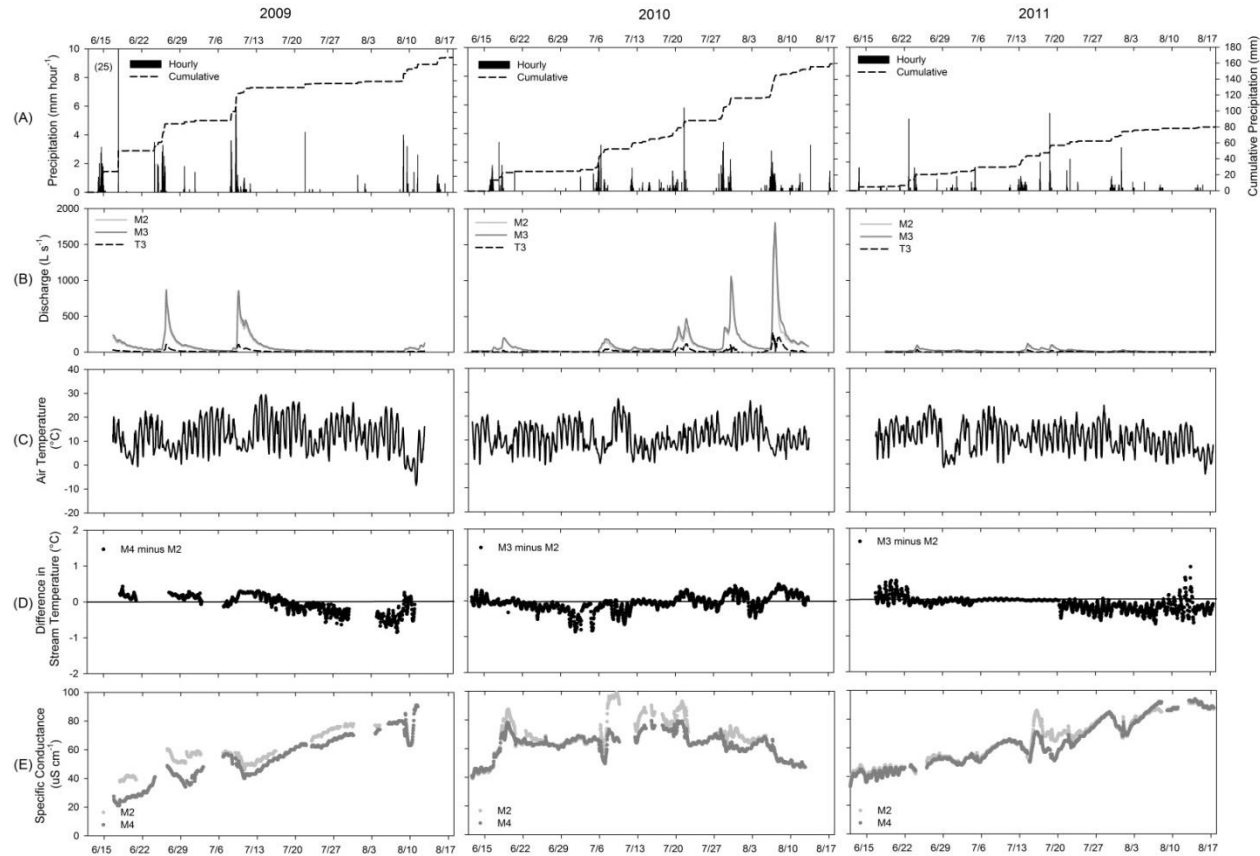


Figure 2. Hydrometeorological conditions in the Reference (M2) and Impacted (M3) reaches of I-minus stream in 2009-2011. (A) Hourly precipitation from weather station located on hillslope adjacent to thermokarst gully feature. (B) Hourly stream discharge. (C) Hourly air temperature from weather station. (D) Difference between Impacted and Reference hourly stream temperatures from HOBO level loggers (except for 2009 Impacted reach where YSI sonde data were used). (E) Specific conductance from YSI sondes (located at M2 and M4).

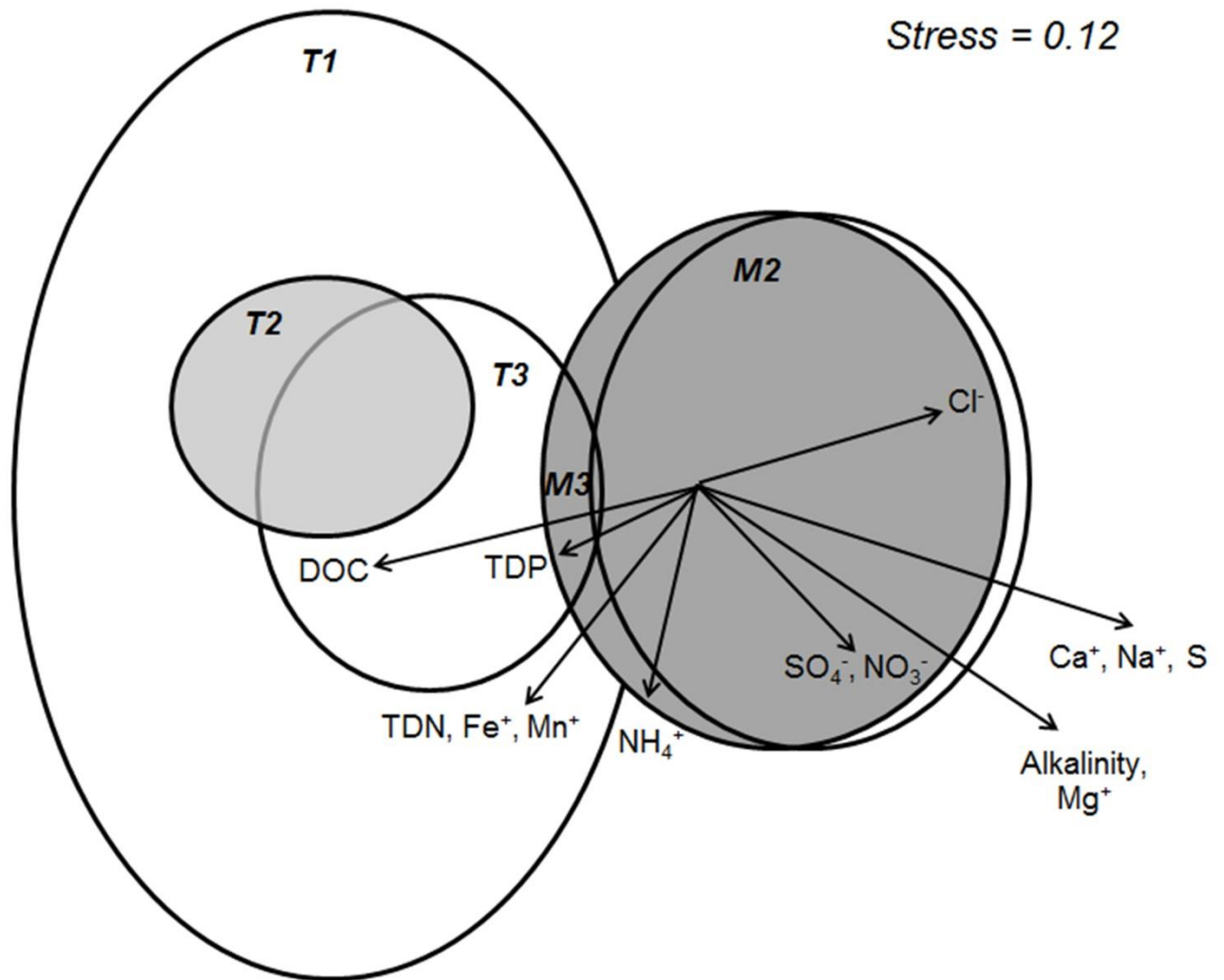


Figure 3. Non-metric multidimensional scaling (NMS) ordination of water chemistry data from 5 sampling locations (T1; T2; T3; T4; T5 in bold italics) grouped by the three study years (2009-2011) based on pairwise similarity estimates (Bray-Curtis). Sample sizes for each location range from Water chemistry variables included are: alkalinity; DOC; NH₄⁺; PO₄⁺; NO₃⁻; TDN; TDP; Ca⁺; K⁺; Mg⁺; Na⁺; Fe⁺; Mn⁻; S; SO₄⁻; and Cl⁻. The overlaid vectors indicate the strength of correlation between water chemistry variables and the clusters within multidimensional space.

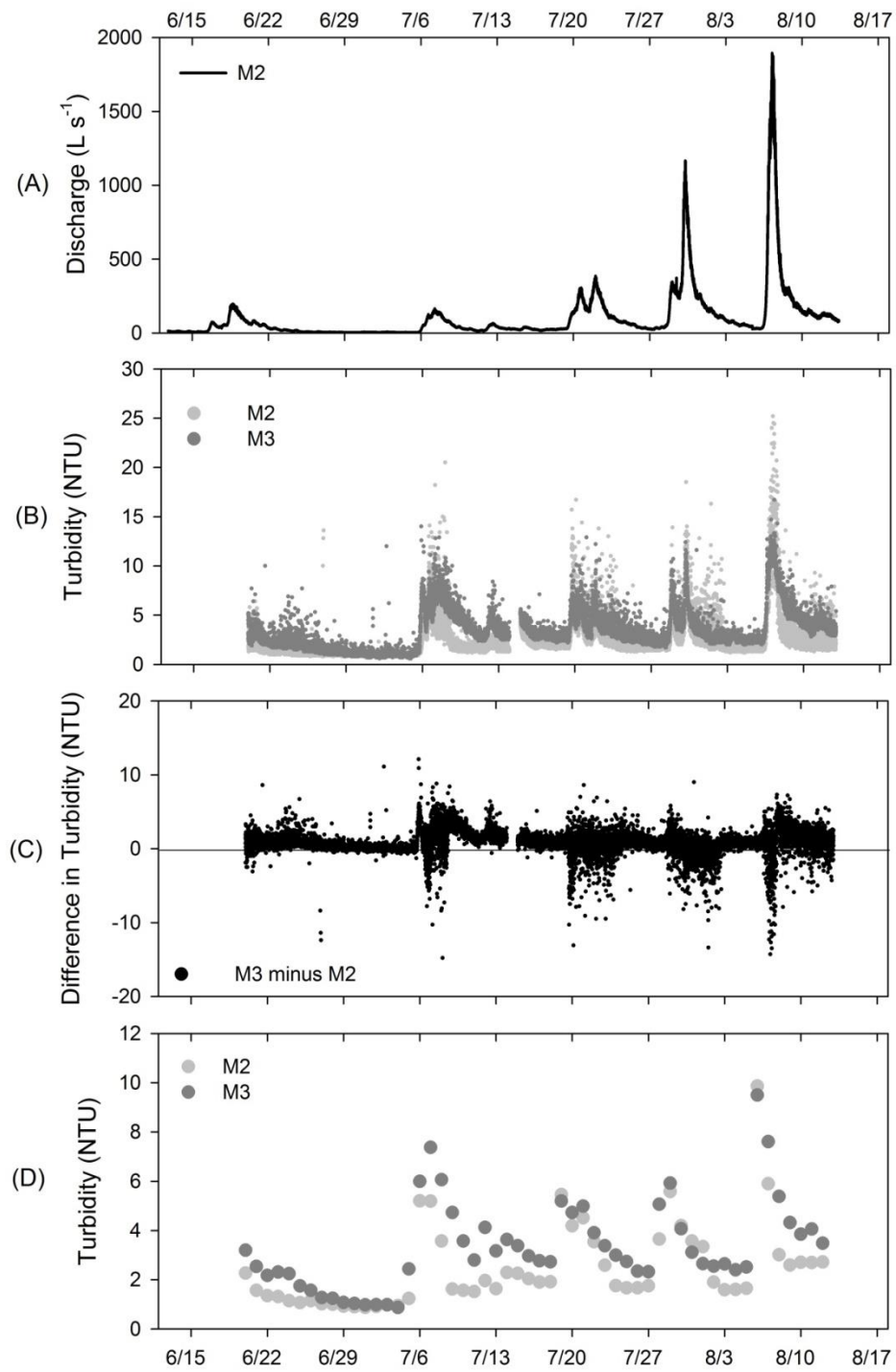


Figure 4. Continuous records of A) 5-minute discharge, B) 5-minute turbidity, C) difference in turbidity, and D) mean daily turbidity for I-Minus Reference (M2) and Impacted (M3) reaches for the 2010 summer season.

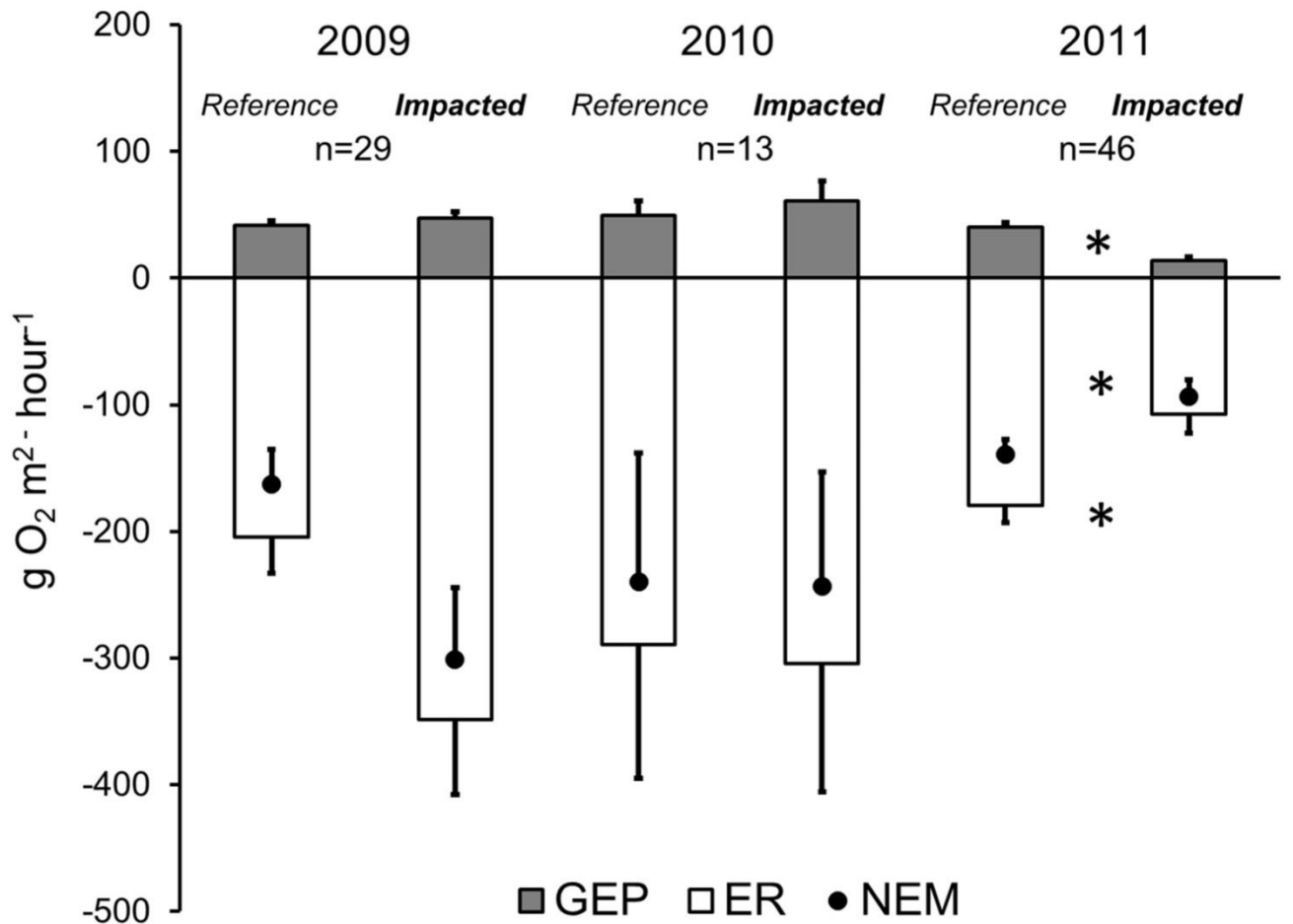


Figure 5. Seasonal mean and standard error of whole-stream metabolism metrics: gross ecosystem productivity (GEP), ecosystem respiration (ER), and net ecosystem metabolism (NEM) of baseflow days for I-Minus Reference and Impacted reaches. Sample sizes for 2009-2011 are 28, 7, and, 46 days, respectively. ‘*’ indicates significant differences (P<0.001).

Supplementary Materials

Supplementary Table 1

Water chemistry analytes and their respective methods, detection limits and instruments

Variable	Method	Instrument
Soluble reactive orthophosphate (PO ₄ ³⁻ -P)	Lachat QuickChem 10-115-01-1-Q	Lachat autoanalyzer
Nitrate (NO ₃ ⁻ -N)	Lachat QuickChem 10-107-06-2-O	Lachat autoanalyzer
Ammonium (NH ₄ ⁺ -N)	Lachat QuickChem 10-107-04-1-B	Lachat autoanalyzer
Dissolved Organic Carbon (DOC)	EPA 415.1 (Combustion)	Shimadzu TOC-V CHP
Total Dissolved Nitrogen (TDN)	Combustion with chemiluminescence	Antec 750
Total Dissolved Phosphorus (TDP)	EPA 365.2	Shimadzu UV-Spectrophotometer 1601120V
Particulate Phosphorus	EPA 356.2	Spectrophotometer Shimadzu UV-1601120V
Particulate Carbon and Nitrogen	Combustion with thermal conductivity	FlashEA NC Soil Analyzer
Base cations	ICP-OES	Perkin Elmer Optima 3000DV
Micronutrients	ICP-OES	Perkin Elmer Optima 3000DV
Metals	ICP-OES	Perkin Elmer Optima 3000DV
Anions	Ion Chromatography	Dionex IonPac AS14A
Alkalinity	Titration	Tim800 ABU900 Autoburette

Supplementary Table 2

Summary of seasonal water quality concentrations and comparisons across sampling locations at I-Minus (2009-2011). Seasonal mean, sample size ($n = \text{days}$), and 1 standard error (SE) are reported. The significance of differences between stream samples across key comparisons (M2 vs. M3; M2 vs. T3; T1 vs. T2; and T1 vs. T3) were tested with Mann-Whitney tests at various levels of α and are reported in Supplementary Table 2. SRP and NH_4 samples from 2009 were analyzed using a different method than in 2010-11 (see details in methods section)

	2009					2010					2011				
	M2	M3	T1	T2	T3	M2	M3	T1	T2	T3	M2	M3	T1	T2	T3
ALK ($\mu\text{eq L}^{-1}$)															
mean	429.9	378.4	61.6	16.8	217.7	396.6	357.4	14.5	19.8	153.7	509.2	501.9	135.7	54.4	258.1
SE	23.9	23.0	17.0	10.2	48.1	8.8	10.4	-	1.3	38.8	69.7	63.7	48.4	4.3	37.6
n	33	33	4	3	4	35	38	1	3	5	7	7	6	7	7
DOC (μM)															
mean	552.0	607.7	1088	956.1	993.6	637.1	674.1	1022	947.6	825.4	419.0	462.1	1429	837.7	677.7
SE	19.0	17.3	53.0	69.3	72.5	28.3	27.4	-	111.3	68.4	40.5	43.4	149.5	70.8	66.3
n	33	33	6	4	5	35	38	1	3	5	7	5	6	7	7
TDP (μM)															
mean	0.13	0.20	0.74	0.14	0.27	0.16	0.13	0.64	0.15	0.14	0.17	0.09	0.60	0.15	0.13
SE	0.01	0.04	0.18	0.01	0.02	0.02	0.02	0.26	0.03	0.06	0.05	0.02	0.30	0.03	0.02
n	32	33	6	4	5	49	48	2	3	5	7	7	6	7	7
SRP (μM)															
mean	0.08	0.13	0.86	0.56	0.08	0.17	0.16	0.10	0.08	0.10	0.09	0.06	0.11	0.06	0.06
SE	0.01	0.05	0.46	0.53	0.02	0.01	0.005	0.01	0.03	0.01	0.01	0.01	0.02	0.02	0.02
n	28	28	6	4	5	49	47	2	3	5	7	7	6	7	7
TDN (μM)															
mean	16.71	16.41	41.35	20.17	23.38	19.74	19.92	26.10	25.57	23.42	15.94	16.42	44.56	23.40	21.71
SE	0.41	0.48	7.78	1.40	2.23	0.53	0.58	-	1.95	0.73	0.88	1.04	10.29	0.70	1.77
n	33	33	6	4	5	35	38	1	3	5	7	5	6	7	7
NH_4 (μM)															
mean	1.24	1.50	13.67	1.09	1.80	2.30	1.78	2.57	0.78	0.87	1.06	1.12	9.35	1.23	1.46
SE	0.08	0.15	4.85	0.13	0.70	0.10	0.09	0.63	0.08	0.08	0.06	0.04	6.42	0.08	0.11
n	31	31	5	4	5	49	47	2	3	5	7	7	6	7	7
NO_3 (μM)															
mean			Non-detect			0.70	0.56	0.20	0.52	0.17	0.52	0.17	0.20	0.30	0.18

	SE						0.11	0.12	0.03	0.02	0.06	0.02	0.06	0.03	0.08	0.03
	n						49	47	5	2	3	2	3	5	6	7
Fe (mg L ⁻¹)	mean	0.23	1.28	1.59	0.71	4.97	0.10	0.24	2.46	0.51	2.82	0.25	0.48	12.05	2.81	6.54
	SE	0.03	0.15	0.37	0.15	2.09	0.004	0.05	1.06	0.18	1.38	0.05	0.10	3.16	0.44	1.24
	n	16	16	5	4	5	48	48	2	3	5	7	7	6	7	7
Mn (mg L ⁻¹)	mean	0.01	0.32	0.24	0.05	1.46	0.008	0.05	0.30	0.03	0.90	0.01	0.10	1.90	0.21	1.59
	SE	0.002	0.04	0.13	0.01	0.59	0.001	0.003	0.14	0.01	0.41	0.004	0.02	0.53	0.03	0.25
	n	16	16	5	4	5	48	48	2	3	5	7	7	6	7	7
TSS (mg L ⁻¹)	mean	0.87	3.53	1183	2.12	38.82	0.87	1.41	121.8	3.08	4.84	0.50	0.40	8.09	6.26	1.69
	SE	0.14	0.95	594	1.00	10.56	0.08	0.13	106.8	-	0.82	0.31	0.35	2.24	4.78	0.55
	n	26	27	4	5	6	25	25	2	1	5	5	5	4	5	5

Supplementary Table 3

Key statistical comparisons of the data reported in Table S1 between main channel and tributary localities using Mann-Whitney Rank Sum tests. The magnitude and direction between the comparisons is simplified with the following symbolic notations: highly significant at the $\alpha \leq 0.001$ level (>>> or <<<<); significant at the $\alpha \leq 0.05$ level (>> or <<<); marginally significant at the $\alpha \leq 0.10$ level (> or <); and approximately equal or no significance (\approx). Empty cell = no data; 'nd' = non-detect; '-' = low sample size

	2009				2010				2011			
	M2:M3	M2:T3	T1:T2	T1:T3	M2:M3	M2:T3	T1:T2	T1:T3	M2:M3	M2:T3	T1:T2	T1:T3
ALK ($\mu\text{eq L}^{-1}$)	\approx	>>	>	<<	>>	>>	-	\approx	\approx	>>	\approx	<<
DOC (μM)	<<	<<<	>	\approx	\approx	>	-	\approx	\approx	<<	>>	>>>
TDP (μM)	\approx	<<<	>>	>	\approx	\approx	\approx	\approx	\approx	\approx	>	>>
SRP (μM)	\approx	\approx	\approx	>>	\approx	\approx	\approx	\approx	\approx	\approx	\approx	\approx
TDN (μM)	\approx	<<	>>	>>	\approx	>	-	\approx	\approx	<<	>>	>>
NH ₄ (μM)	\approx	\approx	>>	>	>>>	\approx	\approx	\approx	\approx	<<	>>	>>
NO ₃ (μM)	nd	Nd	nd	nd	>>	>>	>>	\approx	\approx	>>>	\approx	>>
SO ₄ (μM)	>>	>	\approx	\approx	\approx	>>	\approx	\approx	\approx	>>>	\approx	\approx
Fe (mg L^{-1})	<<<	<<	>>	\approx	<<<	<<	>	\approx	>	<<<	>>	\approx
Mn (mg L^{-1})	<<<	<<	\approx	\approx	<<<	>	-	\approx	<<<	<<<	>>	\approx
TSS (mg L^{-1})	<<<	<<	\approx	\approx	<<<	<<	-	\approx	\approx	>	\approx	>>

Supplementary Table 4

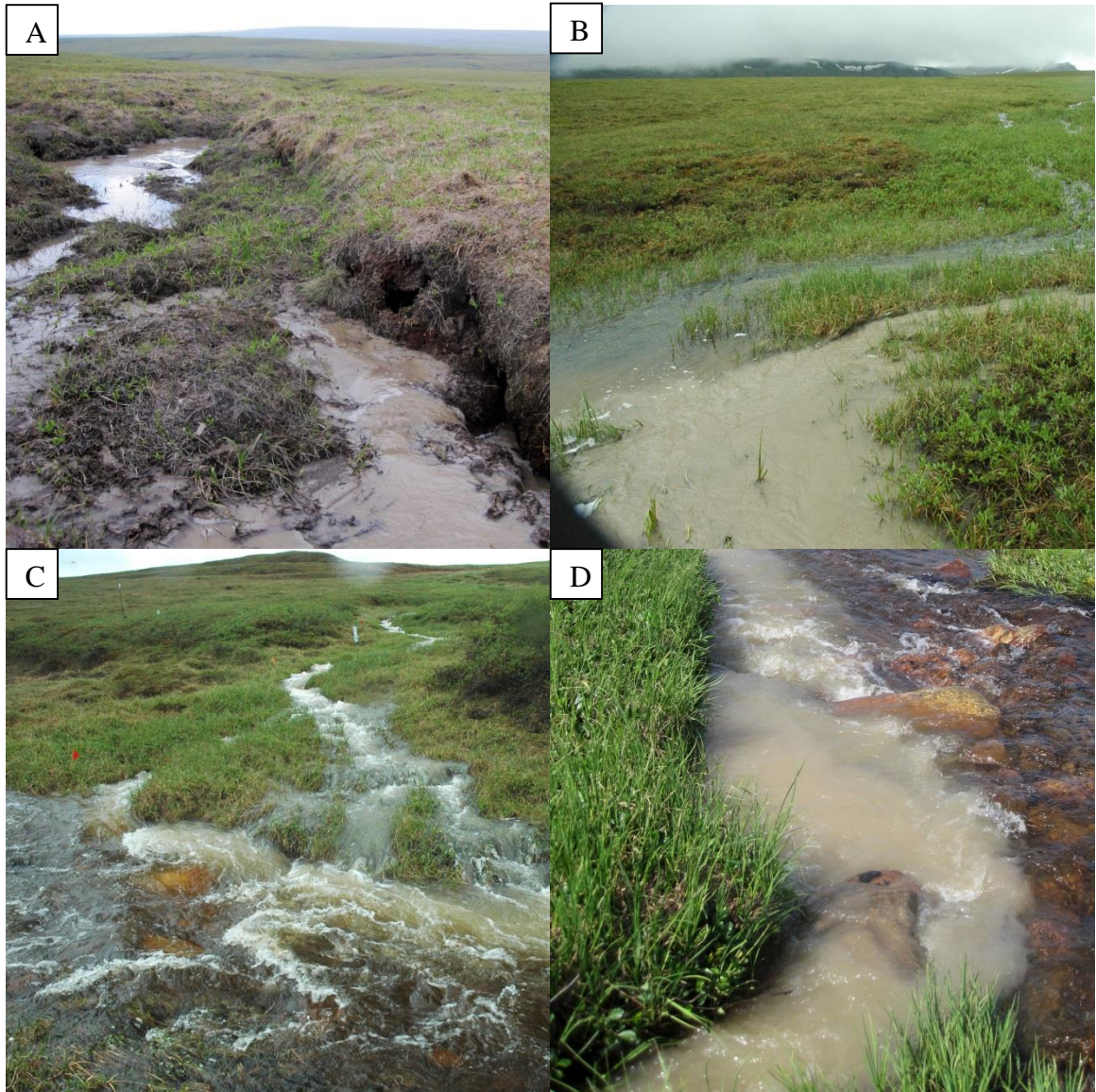
Global R values reported below from the comparisons between sampling locations in the ANOSIM. P-values (not shown) were all significant ($P=0.000$); however we consider any $R>0.3$ to be ecologically significant

	M2	M3	T1	T2
M3	0.15	-	-	-
T1	0.93	0.90	-	-
T2	0.91	0.88	0.35	-
T3	0.88	0.80	0.30	0.26

Supplementary Table 5

Water chemistry variables included in the vector analysis with sample size (N), the correlation between the vector and NMS ordination grouping, and associated probability (P-value) reported

Variable	N	Correlation	P-value
Alkalinity	186	0.91	0.000
DOC	186	0.66	0.000
NH ₄ ⁺	181	0.45	0.000
PO ₄ ⁻	177	0.25	0.009
NO ₃ ⁻	136	0.46	0.000
TDN	186	0.65	0.000
TDP	212	0.34	0.000
Ca ⁺	212	0.90	0.000
K ⁺	212	0.28	0.001
Mg ⁺	212	0.85	0.000
Na ⁺	212	0.89	0.000
Al ⁻	212	0.22	0.012
Fe ⁺	212	0.64	0.000
Mn ⁻	212	0.63	0.000
S	212	0.88	0.000
SO ₄ ⁻	208	0.53	0.000
Cl ⁻	208	0.50	0.000



Supplementary Figure 1. Ground-level site photos at I-Minus gully and main channel from 2009, approximately 4 years after formation. A) The western edge of the gully headwall (high up in the feature above the T1 sampling location); B) confluence of the turbid gully outflow with the clear water track entering from the southeast (below T1 and T2 sampling locations) (photo credit: M. Flinn); C) view facing south up hillslope from the confluence of the lower gully/water track tributary (T3) with I-Minus receiving stream; 4) view facing downstream at the confluence with the gully/water track tributary entering the stream on the true left bank (in between M2 and M3).

**CHAPTER 3: IMPACTS OF A THERMO-EROSIONAL GULLY ON
ECOSYSTEM STRUCTURE AND FUNCTION OF AN ARCTIC
BEADED TUNDRA STREAM, NORTH SLOPE, ALASKA**

Title

Impacts of a thermo-erosional gully on ecosystem structure and function of an arctic beaded tundra stream, North Slope, Alaska

Authors

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Abstract

The biogeochemical characteristics of a beaded tundra stream on the North Slope, Alaska were quantified over three summer seasons (2009-2011) in response to a gully thermokarst feature that formed in 2003. The results indicate that the permafrost disturbance led to modest cumulative seasonal loading of sediment (95-3,800 kg) and dissolved organic carbon (60-1,200 kg) and ammonium (4-8 kg). We found evidence of altered ecosystem structure (benthic standing stocks, algal biomass) and function (stream metabolism), which may be attributable to the previous years' allochthonous gully inputs.

Rates of ecosystem production and standing stocks of benthic chlorophyll-*a* in the impacted reach were significantly higher during the driest of the three summers, but differences in sediment and nutrient loading were not significant. The observed responses in sediment and nutrient loading six to eight years after gully formation were more subtle than expected, likely due to feature stabilization and the dynamics controlling the hydrologic connectivity between the gully and the stream. Nonetheless, we observed significant differences in metabolism and benthic structure, suggesting that even though the geochemical signal diminished upon reaching the receiving stream, gully features may have long-lasting, low-level impacts on the biological characteristics of downstream ecosystem function. Comparison of this beaded stream to a nearby alluvial, cobble-bottom stream that also had a gully thermokarst of about the same size and age suggests that impacts of the thermokarst disturbances were different in the two streams. The differences we observed in benthic chlorophyll-*a* and metabolism are likely related to the different geomorphic forms of these streams.

1. Introduction

Numerous studies have demonstrated the potential of upland thermokarst to export allochthonous sediment, organic matter, dissolved ions, and inorganic nutrients [Bowden *et al.*, 2008; Harms *et al.*, 2014; Kokelj *et al.*, 2005; Kokelj *et al.*, 2009; Lamoureux and Lafrenière, 2009]. However, there is considerable uncertainty about the length of time thermokarst features remain unstable and actively transport sediments and nutrients. Those few studies that have documented thermokarst influence on seasonal

solute concentrations or total fluxes at the catchment scale found that the impact of localized disturbances on hydrologic export is not always discernable [*Lafrenière and Lamoureux, 2013; Lewis et al., 2011*]. Examples of the downstream biological impacts of elevated sediment and nutrient delivery from thermokarst include shifts in Arctic lake food webs due to changes in water transparency and nutrient availability [*Mesquita et al., 2010; Thienpont et al., 2013*] and significant decreases in river ecosystem production and respiration [*Calhoun, 2012*]. With the exception of Larouche et al. (in review), no studies have quantified the impact of thermokarst export on benthic composition and ecosystem processes (i.e., energy flow and nutrient cycling) in headwater tundra streams.

We report the results from a comprehensive 2009-2011 characterization of a tundra stream on the North Slope of Alaska that was impacted by a gully thermokarst gully that formed in 2003. The primary aim was to quantify the enduring impacts of a gully disturbance on key hydrobiogeochemical variables across three summer seasons. *Bowden et al. (2008)* reported that this gully disturbed a 0.9 km² subcatchment and delivered more sediment downslope to the Toolik River when it first formed than is normally delivered in 18 years from a nearby, 132 km², undisturbed catchment (the upper Kuparuk River). We hypothesized that elevated sediment input from the thermokarst, whether persistent or short-lived, would offset the stimulatory effects of introduced allochthonous carbon and nutrients on ecosystem structure and function. We expected to observe diminished quality of benthic resources (e.g., epilithic CNP ratios and algal biomass), as well as reduced ecosystem production, respiration, and nutrient uptake rates.

2. Methods

2.1 Site Description and experimental design

The Toolik River gully thermokarst (Fig. 1) is located at 68.691817 latitude; -149.207767 longitude about 11 miles northeast of Toolik Field Station. The gully formed in 2003 after the collapse of a continuous, downslope void (a tunnel) that formed after an ice wedge melted. A water track above the gully thermokarst delivered water that rapidly erode the ice wedge and subsequently transported sediment down slope to the Toolik River. The Toolik River is a second-order peat-bottom, beaded tundra stream originating approximately three miles southeast of the thermokarst location. Two primary monitoring stations were established (Fig. 1; Table 1) to test for an effect of the thermokarst: one at the Impacted stream reach, downstream of the gully influence (M3) and one at the Reference reach, upstream of the gully (M2). Three hillslope locations (Fig. 1; Table 1) were sampled periodically to characterize the biogeochemical signature of hillslope waters: gully outflow (T1); water track (T2) inputs; and 3) the water directly impacting the receiving stream (T3). Details of the physical characteristics of the primary study reaches can be found in Table 2. The Reference study reach was approximately 260 meters in length upstream of the thermokarst confluence and had a mean width of 2.8 m and a mean depth of 0.4 m with a relatively shallow slope (mean slope 1.4 ± 0.2 %). The Impacted study reach was approximately 240 m in length downstream of the thermokarst input and had a mean width and depth of 3.0 m and 0.6 m, respectively with a lower gradient (mean slope 0.9 ± 0.2 %) compared to the Reference reach. In the 2009-2011

field seasons, the Reference (M2) and Impacted (M3) reaches of the Toolik River were instrumented and sampled as described in Table 3.

2.2 Hydrology and sediment dynamics

Stream stage was monitored in the Toolik River in the Reference reach for summers 2009-2011 and in the Impacted reach for summers 2010-2011, at 5-minute intervals with HOBO water level loggers (Onset Computer Corporation, Inc., Bourne, MA, USA), barometric pressure-corrected and then converted to 5-minute discharge records using a stage-discharge rating curve constructed each summer from current velocity measurements obtained using a FlowTracker Handheld-Acoustic Doppler Velocimeter (SonTek/YSI, San Diego, CA, USA). We attempted to establish the same stage monitoring location each season. All rating curves were with fit with a power function (all R^2 were > 0.97) based on the HOBO stage and FlowTracker discharge measurements.

In the Impacted reach our best estimates of flow were from the rating curve developed in 2010; the rating curves from 2009 and 2011 were not useable. To fill in the discharges in the Impacted reach for these two years we developed a linear relationship between the discharges in the Impacted (downstream) versus the Reference (upstream) reaches in 2010 and then used this relationship to predict the discharges in the Impacted reach in 2009 and 2011 on the basis of the discharge in the Reference reach in 2009 and 2010. Water contributed by the gully feature to the Impacted reach at T3 (Fig. 2b) was calculated to be the difference in stream flow between M3 and M2 gauged locations, assuming no hillslope water was lost or gained between T3 and M3 locations. We note

that this approach is potentially circular for the 2009 and 2011 calculations. However, we measured flow from T3 a limited number of times (too few to construct a rating curve) using a salt-dilution gauging method (Kilpatrick and Cobb, 1985; Wlostowski, Gooseff, and Wagener, 2013) and found a good correspondence between flow measured by the dilution method and flow estimated by the difference between the Reference and Impacted measured flows.

To determine changes in suspended sediment due to thermokarst input, we measured total suspended sediment (TSS) in the Reference and Impacted reach using standard methods (USGS method I-3765). For each sample, a known volume of stream water was filtered in the field through a pre-dried (105°C) and pre-weighed 47-mm diameter glass fiber filter (GF/F) and re-dried and re-weighed. TSS was calculated as the difference in filter mass before and after filtration divided by the volume filtered (mg L^{-1}). Turbidity sensors (DTS-12 from FTS Environmental, Victoria, BC, Canada) were installed in conjunction with automated ISCO samplers (Teledyne ISCO, Lincoln, NE, USA) to collect 5-minute turbidity measurements in the Reference and Impacted reaches for the 2010 season only.

2.3 Hydrochemistry

Water samples for chemical analyses were collected with an ISCO autosampler (daily composite stream samples collected four times per 24 hours at 00:00; 06:00; 12:00; 18:00) at the M2 and M3 stations in 2009 and 2010. Grab water samples were taken opportunistically from hillslope locations (T1, T2, T3) 2009-2011 and stream water grab samples were taken biweekly from the Reference and Impacted reaches in 2011 since the

ISCO samplers were not used in 2011. Seasonal mean values were calculated using daily (2009 and 2010) or biweekly (2011) measurements. All water samples were filtered through pre-combusted (450°C) 25-mm diameter GF/Fs with a nominal pore size of 0.07 μm , with the exception of the water designated for base cation analyses, which were filtered with nylon syringe filters with a pore size of 0.45 μm . Separate samples were taken for each analyte. Samples for soluble reactive ortho-phosphate (SRP or $\text{PO}_4^{3-}\text{-P}$), nitrate ($\text{NO}_3^- \text{-N}$), and ammonium ($\text{NH}_4^+ \text{-N}$) were frozen; samples for DOC (dissolved organic carbon), TDN (total dissolved nitrogen), TDP (total dissolved phosphorus); and base cations (calcium, Ca^{2+} ; magnesium, Mg^{2+} ; potassium, K^+ ; and sodium, Na^+); micronutrients and metals (aluminum, Al; iron, Fe; manganese, Mn; boron, B; copper, Cu; zinc, Zn; sulfur, S; strontium, Sr; lead, Pb; nickel, Ni; chromium, Cr; and cadmium, Cd) were acidified with 100 μl 6N hydrochloric acid for every 50-mL of sample; and anions (chloride, Cl^- and sulfate, $\text{SO}_4^{2-}\text{-S}$) and alkalinity samples were refrigerated. Samples were shipped back to the University of Vermont in Burlington, Vermont; the Ecosystems Center in Woods Hole, Massachusetts; or the University of Michigan for analysis within six to nine months. Table 4 summarizes the methods and instruments used for water chemistry analyses.

2.4 Benthic characterization

Epilithic chlorophyll-*a* (chl-*a*) and epilithic particulate CNP were quantified at four riffle stations along the Reference (M1-M2) and Impacted (M3-M4) reach to provide an integrated, reach-scale average estimate. These reach-averaged metrics were calculated six times across each summer period (2009-2011) to generate mean seasonal

epilithic standing stocks of CNP and chl-*a*. The method utilized to obtain epilithic chl-*a* and particulate CNP followed the ‘whole-rock’ scrub method (Peterson et al., 1993) and involved scrubbing the epilithic material with a wire brush from the entire surface, top and bottom, of rocks sufficient to cover the bottom of a dishpan of a known area and then rinsed into a known volume of stream water. One dishpan whole-rock scrub was completed at each of the four riffle stations resulting in four bottled scrubate samples from each reach. Scrubate was collected in 250-mL amber bottles to prevent further photosynthetic activity and transported back to TFS or base camp. A known amount of epilithic slurry was filtered onto four 25-mm diameter GF/Fs: two for chl-*a*, one for particulate phosphorus (PP) and the fourth for particulate carbon (PC) and nitrogen (PN) analyses. The duplicate chl-*a* filters were extracted in MgCO₃-buffered 90% acetone in the dark on ice for 18-24 h (Strickland and Parsons, 1968) and total chl-*a* was measured fluorometrically using a Turner Designs 10-AU fluorometer (Turner Designs, Incorporated, Sunnyvale, CA, USA). The PP and PCPN filters were dried overnight at 50°C, stored in petri dishes for particulate CNP analyses.

2.5 Stream metabolism

We quantified the net daily metabolism of the Reference and Impacted reach for each gully site from mid-June through mid-August in each of the three years of this study (2009-2011). Whole-stream metabolism (WSM) estimates were based on an open-channel, single station approach [Bott, 1996; Houser et al., 2005; Marzolf et al., 1994] using continuous records of dissolved oxygen (DO) and temperature at 5-min intervals measured by 600-OMS V2 Multi-parameter Water Quality Sondes (YSI Incorporated,

Yellow Springs, OH, USA). One sonde was placed at the bottom of the Reference and Impacted reach and were calibrated every two weeks in the field and ensured that the two sondes at each thermokarst site read within 1% of the other.

The WSM analysis followed the common approach of *Bott* (1996) modified for the Arctic environment (i.e., 24-hr light) following that of *Cappelletti* (2006) and utilized an R-script written for this purpose. This script calculates WSM metrics in units of $\text{g O}_2 \text{ m}^{-2}$ and reports gross ecosystem production (GEP), ecosystem respiration (ER); and net ecosystem production (NEP). The model distinguishes a nighttime period based on a light threshold of 1% and produces an interpolated ER baseline at 0% light. The model solves an optimization of the [*Platt and Jassby*, 1976] photosynthesis-irradiance equation to model NEP on a daily basis. The Energy Dissipation Model [*Tsivoglou and Wallace*, 1972] equation is used to calculate a reaeration coefficient (k) for each data interval based on velocity, which is derived from a function of discharge. Seasonal means of NEP, CR, and GPP were reported from daily estimates during baseflow conditions as defined by a mean flow or probability of exceedance of 10% from a combined flow duration curve (not shown) from all three years ($Q \leq 171 \text{ L s}^{-1}$).

2.6 Statistical Analyses

For all analyses, we evaluated normality with normal probability plots and equal variance with Levene's test [*Levene*, 1960]. Those data that passed normality and equal variances, differences between Reference and Impacted reaches were compared using one-way ANOVA analyses. Those data that could not be transformed into a normal distribution and did not pass the Levene's test for equal variance were compared using

non-parametric Mann-Whitney Rank Sum tests. Normality plots, equal variance tests, and ANOVA and non-parametric analyses were performed with JMP Pro software (v11) [SAS Institute Inc., 2012]. We considered a range of p-values to be indicative of a notable trend: $\alpha = 0.001$ as highly significant; $\alpha = 0.05$ as significant; and $\alpha = 0.10$ as marginally significant.

We used non-metric multidimensional scaling (NMDS) and Analysis of Similarity (ANOSIM), both formalized by [Clarke, 1993] to test for differences in water chemistry based on Bray-Curtis dissimilarities [Bray and Curtis, 1957]. We selected the NMDS ordination that had the least amount of stress (goodness of fit) and was easiest to interpret. We tested for differences in rank dissimilarity between *a-priori* defined groups using ANOSIM. We considered a comparison with an R value greater than 0.5 to be ‘ecologically significant’. If a p-value was significant ($p < 0.01$), but was associated with an R value less than 0.5, the comparison was considered not important. We used a vector analysis to overlay water chemistry variables to the ordination to help determine which factor was contributing to differences (strength of correlation and direction) in *a-priori* groupings. We did not include vectors with correlation coefficients below 0.5 even if the variable had a significant p-value because they did not help us interpret the multivariate clusters. DECODA (Database for Ecological COmmunity DAta) version 3 [Minchin, 1990] was used to perform the multivariate analyses (NMDS, ANOSIM, and vector analysis).

3. Results

3.1 Hydrology and sediment dynamics

The weather conditions and hydrological dynamics were different across the three study seasons (Figures 3A and 3B) at the Toolik River. The summers of 2009 and 2010 were characterized by variable weather patterns with two and four notable precipitation events, respectively. The summer of 2011 was extremely dry with very low stream flow compared to the first two years in the three-year dataset. Hydrographs during the three study seasons were typical of an arctic runoff regime with fast response times and extended recessions. There were two, four, and zero distinct storm events during 2009, 2010 and 2011 field seasons, respectively (Figure 2B).

We did not find significant relationships between stream discharge and turbidity or TSS (data not shown). Seasonal mean TSS concentrations in the Impacted reach were significantly greater than Reference reach concentrations in 2009 ($P < 0.001$) and 2010 ($P = 0.03$), but not in 2011 ($P = 0.66$), the low flow year (Table 6). Absolute TSS loading in the Impacted reach (concentration multiplied by discharge) was approximately double the loading of the Reference reach in 2009 and 2010, and nearly identical in 2011 (Table 5). Seasonal mean daily turbidity measured in 2010 was significantly higher in the Impacted (4.23 ± 0.16 NTU, $n = 56$) compared to the Reference (3.22 ± 0.16 SE NTU, $n = 56$, $P < 0.0001$) (Figure 5D). The five-minute data record shows that the Impacted reach exceeded the Reference reach during baseflow and peak storm periods, although there was more variability in the difference between the two reaches during storms (Figures 5B and 5C). Daily turbidity in the Impacted reach was on average approximately 1 NTU

greater than daily turbidity in the Reference reach across the entire season and was approximately 2.5 and 5.5 NTU higher during 2 out of the 5 events in 2010. The largest discrepancies in daily mean turbidity between the reference and impacted reaches occurred during high discharge events, but the particular day of the discrepancy varied across the rise, peak, and recession of each storm. The day preceding a storm event on 28 June 2010, the mean turbidity in the Impacted reach exceeded the turbidity in the Reference by 3.0 NTU suggesting that possibly another mechanism other than storm events may deliver sediment from thermokarst receiving streams (i.e., high air temperatures or a collapse within the feature). There is a gravel road that crosses upstream of the Reference reach and there has been other thermokarst activity observed in the vicinity, thus we cannot rule out that there are sediment inputs from upstream that occasionally impact our Reference reach.

3.2 Hydrochemistry

The primary sampling stations at the Toolik River site allow a comparison of nutrient loading at different scales from undisturbed and disturbed tundra locations. Comparing the main channel and tributary stations (Figure 1) provides information about the magnitude of the thermokarst disturbance relative to the characteristics of the main river channel, on a fairly small scale (< 5 km²). Comparison of T2 vs T1 describes differences between water flowing from a beaded stream in undisturbed tundra above the headwall of the thermokarst and water flowing out of the main portion of the thermokarst feature (i.e., likely a combination of new melt water arising from permafrost and the water from above the headwall). Comparison of T1 vs. T3 shows if there is an effect on

the water as it travels down the hillslope from the thermokarst disturbance to the receiving main channel. Comparison of M2 vs. T3 indicates whether the hillslope outflow has a unique signature compared to the upstream main channel. Finally, comparison of M2 vs M3 indicates whether there is an immediate impact of the low hillslope tributary (T3) on the characteristics of the main river flow immediately downstream.

Table 6 reports the seasonal mean concentrations of a suite of hydrochemistry variables for each sampling location. We compared the upstream (Reference, M2) and downstream (Impacted, M3) sampling locations across all water chemistry variables for each year since they were the only two localities with equal sample sizes (the bold type face indicates a statistically greater seasonal mean concentration at $\alpha = 0.05$ level). The daily mean specific conductance of the Impacted (M4) reach was significantly higher ($33.1 \pm 0.97 \mu\text{S cm}^{-1}$, $n=52$) than that of the Reference (M2) reach ($29.9 \pm 0.98 \mu\text{S cm}^{-1}$, $n=52$, $P=0.02$) in 2009 only.

The differences in area-specific loadings among biogeochemical variables between the Reference and Impacted reach were typically relatively small (Table 5). TSS and SRP area-specific loadings were greater in M3 compared to M2 in 2009; TSS, SRP and $\text{NO}_3\text{-N}$ were greater in 2010; and there were insignificant differences in any of these variables in 2011. Impacted reach absolute loadings were typically higher than the Reference reach, primarily due to greater discharge. Rainfall in 2009 and 2010 produced elevated discharge and therefore the flux of all solutes in both reaches.

In general, the outflow of the gully thermokarst (T1) contained high concentrations of TDP, SRP, TDN, NH_4 , NO_3 , and TSS compared to the water track

above the headwall of the thermokarst (T2) and the receiving stream (M2 and M3) (Table 6). The NMDS analysis visualizes the (dis)similarities in water chemistry among the five localities. The hydrochemistry characteristics of the Reference and Impacted reaches were not significantly different (Figure 4; ANOSIM $R = 0.08$ $P = 0.000$, Table 8) despite the hillslope locations (T1, T2, and T3) having significantly different biogeochemical signatures when each are compared to M2 and M3 (Figure 4; ANOSIM R values ranges from 0.58 to 0.92; Table 8). The centroids for the T1, T2 and T3 data clusters are distinct from centroids of the M2 data cluster as well as the M3 data cluster. As expected, the T3 centroid overlaps both T1 and T2. The water chemistry of the thermokarst outflow (T1) is significantly different compared to the water track above the headwall (T2) (ANOSIM $R = 0.51$ $P=0.000$; Table 8). The comparison between T1 versus T3 and T2 versus T3 are not different (ANOSIM $R = 0.19$ and $R = 0.34$, respectively, Table 8), and expected given that T3 is a combination of both T1 and T2 water.

3.3 Epilithic chlorophyll-*a* and CNP standing stocks

Epilithic chlorophyll-*a*, a measure of autotrophic biomass, was significantly higher in the Impacted reach compared to the Reference in 2009 ($P=0.01$) and 2011 ($P=0.01$) by a factor of two (Table 7). Standing stocks of carbon, nitrogen and phosphorus were approximately equal between the two reaches. In general, epilithic molar ratios, an indication of basal resource quality were not different between the two reaches except for significantly greater C:N in 2009 in the Reference ($P=0.02$), significantly greater C:N in the Impacted reach in 2010 ($P=0.005$) (Table 7).

3.4 Whole-stream metabolism

Seasonal mean rates of gross ecosystem production (GEP), ecosystem respiration (ER), and net ecosystem metabolism (NEM) did not differ significantly between the Reference and Impacted reaches in 2009 or 2010 (Figure 6). In 2011, seasonal mean GEP was significantly greater in the Impacted reach ($0.98 \pm 0.34 \text{ g m}^{-2} \text{ d}^{-1}$, $n=53$) compared to the Reference ($0.36 \pm 0.26 \text{ g m}^{-2} \text{ d}^{-1}$, $n=32$, $P < 0.0001$) and NEM was also significantly greater in the Impacted reach ($-1.57 \pm 0.43 \text{ g m}^{-2} \text{ d}^{-1}$, $n=53$) compared to the Reference ($-2.09 \pm 0.53 \text{ g m}^{-2} \text{ d}^{-1}$, $n=32$, $P < 0.0001$) (Figure 6). Seasonal mean reaeration fluxes were significantly greater ($P < 0.0001$) in the Reference reach across all seasons (data not shown). There is a strong linear correlation between the predicted rates of NEM based on the optimization model of the Jassby-Platt photosynthesis-irradiance equation to the observed WSM field DO data, indicating that the model fits the data appropriately (data not shown). The seasonal mean GEP/ER ratios across 2009-2011 for the Reference reach were -0.25, -0.31, and -0.14 (note that these values are negative because we have chosen to express ER consistently as a negative number), respectively, while the Impacted mean GEP/ER ratios were -0.31, -0.66, and -0.38 and all were significantly different ($P < 0.0001$, ANOVA) between the two reaches across all years.

4. Discussion

4.1 Sediment and nutrient export

In recent studies of Arctic aquatic systems, researchers concluded that thermokarst activity had contrasting impacts on sediment and nutrient loading to downslope ecosystems. Conclusions with respect to sediment loading following

permafrost disturbance ranged from substantial and persistent [Bowden *et al.*, 2008; Calhoun, 2012] to short-lived or minimal [Dugan *et al.*, 2012]. We hypothesized that sediment concentrations and fluxes would increase in the Impacted reach and we found that measureable sediment loading can persist 6-8 years after initiation of the thermokarst. However, similar to other studies [Lafrenière and Lamoureux, 2013], our study indicates that increase in downstream sediment and turbidity were largely dependent on the degree of seasonal storm activity to mobilize and connect hillslope sediment from the gully to the stream. Area-specific sediment loadings from the thermokarst tributary (T3) were substantially greater compared to the mainstem locations (M2 and M3) during the wetter years monitored (2009 and 2010). Absolute sediment loading from T3 in 2009 was twice the magnitude of the Reference reach, causing a doubling of the Impacted sediment load. Sediment loading from the T3 subwatershed in 2010 was lower compared to the previous season, but still caused the Impacted reach loading to be twice the magnitude of the Reference. During the dry 2011 season, there were no discernible effects on sediment in the Impacted reach, probably because there was insufficient water on the tundra to mobilize any sediment from the thermokarst.

We found that the water flowing directly out of the gully (T1) tended to have elevated concentrations of some nutrients: TDP, SRP, TDN, NH₄, NO₃ (Table 6). However, the overall loading from the feature to the Toolik River (T3) is small relative to the total flux of nutrients in the receiving stream (Table 5) since we did not find large differences in concentrations or loadings between the upstream and downstream reaches (M2 and M3). The NMDS analysis (Figure 4) reveals a nuanced mechanism of how the

position on the hillslope may impact the signature of the water before entering the receiving stream. The Toolik River mainstem chemistry is distinct from chemistry at any of the hillslope locations. The gully outflow (T1) signature is significantly different than the reference water (T2) flowing into the headwall of the gully, yet as the water flows and percolates the short distance (~300 m) between the gully and the mainstem, the signature of the T3 water shifts to resemble more of a stream water chemistry profile (i.e., T3 is less different than T1 and T2 are compared to the mainstem). It appears that nutrients exported from the feature may be transformed (i.e., taken up and/or mineralized) by hillslope vegetation and soil microbes. Thus, the hydrologic connectivity (i.e., the presence and frequency of storm events and the distance between the hillslope feature and stream) may play an important role by buffering and regulating the impact of thermokarst outflow entering the receiving stream as riparian areas between feature and stream may sequester nutrients and trap sediments.

This study tracked the evolution of the gully impact into the latter stages of recovery. Large quantities of sediment and nutrients were exported from this feature when it first formed in 2003 [Bowden *et al.*, 2008] and remained elevated in the thermokarst outflow (T3) and Impacted stream (M3) in the first few years following the disturbance [Bowden *et al.*, 2014]. This study indicates that the sediment and the nutrient export, while elevated above reference reach levels, was not remarkably high and did not have a substantial impact on downstream export within a decade post-disturbance (Table 5). The reduction in sediment and nutrient export is consistent with the rate of recovery and stabilization of the Toolik River gully thermokarst feature [Bowden *et al.*, 2014].

4.2 Impacts on stream function

We hypothesized that the negative effects of sediment deposition would overwhelm the stimulatory effects of nutrient loading from the gully. In contrast, we found that benthic chlorophyll-*a* was significantly greater in the Impacted reach in 2009 and 2011 and that Impacted reach GEP was significantly higher in 2011. Rates of GEP and ER were lower in both reaches during the dry season of 2011 compared to 2009 and 2010. This observation is surprising because it has been shown that mean residence time is inversely correlated with discharge in arctic tundra streams [Zarnetske *et al.*, 2007], potentially permitting greater interaction between the stream biota and in-stream nutrients during low flow conditions. Interestingly, Merck *et al.* (2012) monitored flow paths in another arctic beaded stream and found that dry conditions with low flows facilitated greater in-pool storage and increased water residence time due to strong thermal stratification of cool water in the bottom layers of the pools (beads). It is possible that the colder temperatures at the bottom of stratified pools dampened rates of metabolism during the low flow season.

5. Conclusions and Implications

To quantify the impacts of climate change on stream biogeochemistry in arctic watersheds, it is important to quantify how potential alterations in sediment and nutrient export from thermokarst disturbances vary between types of feature morphologies and across space (i.e., position on the landscape in relation to hydrologic networks) and time (i.e., duration of impact from initial disturbance) [Abbott *et al.*, in review; Kokelj and Jorgenson, 2013; Lafrenière and Lamoureux, 2013]. A survey of hydrologic outflow

from 83 thermokarst across Arctic Alaska concluded that the magnitude and duration of thermokarst effects on water chemistry differed by feature type and secondarily by landscape age, and although most solutes returned to undisturbed concentrations after feature stabilization, some constituents such as dissolved organic carbon, inorganic nitrogen, and sulfate concentrations remained elevated through stabilization for thaw slumps and gully thermokarst [Abbott et al., in review]. The impact of thermokarst features on the hydrologic export of important inorganic solutes and nutrients to downslope arctic aquatic ecosystems depends on various factors: the magnitude and intensity of the initial disturbance and rate of recovery [Kokelj et al., 2005; Lafrenière and Lamoureux, 2013; Thienpont et al., 2013]; the relative hydrologic connectivity of the disturbance [Lafrenière and Lamoureux, 2013]; and other factors unrelated to thermokarst such as physiographic basin characteristics and inter-annual meteorological conditions [Lewis et al., 2011].

The most important finding from this study is that arctic stream ecosystems may be more resilient to the direct perturbations of thermokarst features than we expected when we first began this work. We can demonstrate that there are significant influences of both sediment and nutrient loading from features (i.e., high concentrations measured in outflow), but the age and activity of the feature and the hydrologic connectivity between the feature and its receiving stream are important factors that determine the nature and the magnitude of the impacts on downstream reaches. The impact on water quality is more ephemeral than previously expected, but that the legacy impacts of sediment and nutrient loading immediately after disturbance may have lasting impacts on the biological aspects

(e.g., benthic structure and function) of receiving streams. Results from this study provide insight into the contribution of a gully thermokarst in the latter stages of recovery on solute concentrations and fluxes and concomitant impacts on ecosystem processes in the most abundant stream type on the North Slope, a key first step to scaling and quantifying the impact of climate change on stream biogeochemistry in Arctic watersheds.

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Table 1

Sampling location descriptions, GPS coordinates, and contributing watershed areas of the Toolik River hillslope thermokarst tributary and main stem locations of receiving stream

ID	Description	Latitude (DD)	Longitude (DD)	Watershed area (km ²)
M1	Reference reach, upper	68.694433	-149.200021	-
M2	Reference reach, just above TK confluence	68.695697	-149.204827	11.54
M3	Impacted reach, just below TK confluence	68.695545	-149.207784	12.62
M4	Impacted reach, lower	68.695490	-149.210789	-
T1	Outflow from TK gulley feature	68.692066	-149.207319	1.27
T2	Hillslope water track, above TK headwall	68.690698	-149.208310	1.22
T3	TK water track low, before entering stream	68.693837	-149.205866	1.32

Table 2

Physical characteristics of Toolik River study site. Mean \pm standard error are reported

Metric	Reference Reach (M1 – M2)	Impacted Reach (M3 – M4)
Reach width (m)	2.8 \pm 0.4	3.0 \pm 0.6
Reach depth (m)	0.4 \pm 0.05	0.6 \pm 0.05
Total reach length (m)	260	240
Reach slope (%)	1.4 \pm 0.2	0.9 \pm 0.2
Reaeration coefficient (k in day ⁻¹)		
2009	33.9 \pm 4.0	22.4 \pm 2.5
2010	41.2 \pm 4.9	32.6 \pm 3.2
2011	10.9 \pm 0.4	7.8 \pm 0.3

Table 3*Sampling scheme*

Instrumentation	Purpose
Teledyne ISCO autosamplers YSI sensors	Daily composite water samples for water quality metrics 5 minute logging of water temperature, dissolved oxygen (for whole-stream metabolism), and electrical conductivity
Onset HOBO level loggers ^a	5 minute logging of stream stage for discharge
<i>Manual Sampling</i>	<i>Purpose</i>
Geomorphic survey	To characterize geomorphic characteristics of each reach
Grab water sampling (bi-weekly)	To compare to ISCO autosampler water and to characterize the chemistry of the thermokarst drainage water
Epilithic Rock Scrubs (bi-weekly)	To characterize the benthic communities (algal biomass via chlorophyll- <i>a</i> , particulate elements)

Table 4*Water chemistry analytes and their respective methods and instruments*

Variable	Method	Instrument
Soluble reactive orthophosphate (PO ₄ ³⁻ -P)	Lachat QuickChem 10-115-01-1-Q	Lachat autoanalyzer
Nitrate (NO ₃ ⁻ -N)	Lachat QuickChem 10-107-06-2-O	Lachat autoanalyzer
Ammonium (NH ₄ ⁺ -N)	Lachat QuickChem 10-107-04-1-B	Lachat autoanalyzer
Dissolved Organic Carbon (DOC)	EPA 415.1 (Combustion)	Shimadzu TOC-V CHP
Total Dissolved Nitrogen (TDN)	Combustion with chemiluminescence	Antec 750
Total Dissolved Phosphorus (TDP)	EPA 365.2	Shimadzu UV-Spectrophotometer 1601120V
Particulate Phosphorus	EPA 356.2	Spectrophotometer Shimadzu UV-1601120V
Particulate Carbon and Nitrogen	Combustion with thermal conductivity	FlashEA NC Soil Analyzer
Base cations	ICP-OES	Perkin Elmer Optima 3000DV
Micronutrients	ICP-OES	Perkin Elmer Optima 3000DV
Metals	ICP-OES	Perkin Elmer Optima 3000DV
Anions	Ion Chromatography	Dionex IonPac AS14A
Alkalinity	Titration	Tim800 ABU900 Autoburette

Table 5

Summary of area-specific and absolute cumulative solute mass flux for 3 sampling locations at Toolik River (2009-2011). Sample sizes for solutes 2009-2011 are , and days, respectively. Flux estimates from sampling points (T1) and (T2) are not reported due to lack of reliable flow data from the hillslope locations

		Toolik River 2009-2011					
		Area-Normalized Loading (kg km ⁻²)			Absolute Loading (kg)		
Year	Metric	REF	IMP	TK LOW	REF	IMP	TK LOW
2009	DOC	530	592	822	6112	7477	1085
	SRP	0.21	0.21	0.69	2.42	2.69	0.91
	NH ₄	1.1	1.4	6.6	12.5	18.2	8.7
	NO ₃	-	-	-	-	-	-
	TSS	167	338	2919	1931	4269	3853
2010	DOC	653	659	929	7534	8318	1227
	SRP	0.11	0.21	0.29	1.25	2.68	0.39
	NH ₄	1.0	1.2	3.5	11.3	15.6	4.7
	NO ₃	0.00	0.24	6.5	1.0	3.1	8.6
	TSS	94	148	462	1082	1862	610
2011	DOC	13.4	15.6	45	155	197	59
	SRP	0.003	0.005	0.009	0.04	0.06	0.01
	NH ₄	0.04	0.03	0.09	0.41	0.38	0.12
	NO ₃	0.004	0.003	0.07	0.04	0.04	0.10
	TSS	5.6	5.4	73	65	68	96

Table 6

Summary of seasonal water quality concentrations and comparisons across sampling locations at Toolik River (2009-2011). Seasonal mean, sample size (n = days), and 1 standard error (SE) are reported

	2009					2010					2011				
	REF M2	IMP M3	TK MID T1	TK ABOVE T2	TK LOW T3	REF M2	IMP M3	TK MID T1	TK ABOVE T2	TK LOW T3	REF M2	IMP M3	TK MID T1	TK ABOVE T2	TK LOW T3
ALK (ueq L⁻¹)															
mean	175	185	677	-	527	175	180	319	19	585	218	232	10858	48	4570
SE	14	16	549	-	310	8	11	303	3	186	59	46	731	9	2152
n	25	26	2	-	3	33	34	3	3	6	7	7	2	7	5
DOC (uM)															
mean	939	990	1005	1111	1007	1223	1230	1376	1638	1270	929	942	1496	1791	1372
SE	16	17	99	161	104	31	31	229	221	115	30	28	19	285	294
n	28	27	4	3	4	33	34	3	3	6	7	7	2	7	5
TDP (uM)															
mean	0.29	0.26	0.71	0.17	0.48	0.28	0.23	0.48	0.23	0.34	0.27	0.32	0.37	0.43	0.33
SE	0.05	0.04	0.43	0.03	0.09	0.02	0.01	0.34	0.03	0.03	0.04	0.05	0.03	0.11	0.13
n	27	27	4	4	4	51	50	3	6	6	7	7	2	7	5
SRP (uM)															
mean	0.14	0.14	0.98	0.28	0.33	0.08	0.14	0.24	0.13	0.14	0.09	0.09	0.22	0.09	0.09
SE	0.03	0.03	0.78	0.13	0.10	0.003	0.004	0.08	0.02	0.02	0.02	0.01	0.10	0.02	0.01
n	27	27	4	5	4	50	50	3	6	6	7	7	2	7	5
TDN (uM)															
mean	24.1	23.2	35.7	24.8	33.5	35.2	36.4	47.7	39.4	46.7	33.8	34.6	45.1	39.4	43.2
SE	0.6	0.7	7.7	5.3	6.5	0.5	0.5	11.0	3.6	4.7	1.1	2.0	0.6	4.3	5.3
n	28	27	4	3	4	33	34	3	3	6	7	7	2	7	5
NH₄ (uM)															
mean	1.66	2.07	8.23	1.34	6.91	1.54	1.83	4.45	1.01	3.83	1.93	1.38	0.84	1.22	2.15
SE	0.13	0.16	2.10	0.27	1.30	0.17	0.35	3.13	0.07	1.17	0.26	0.14	0.06	0.16	1.10
n	21	21	4	5	4	50	50	3	6	6	7	7	2	7	5
NO₃ (uM)															
mean						0.14	0.35	8.31	0.37	7.03	0.19	0.16	0.11	0.33	1.78
SE			Non-detect			0.01	0.04	7.45	0.03	3.08	0.04	0.05	0.01	0.06	1.19
n						50	50	3	6	6	7	7	2	7	5
Fe (mg L⁻¹)															
mean	0.93	1.31	1.92	0.98	2.66	1.80	1.81	1.39	3.42	2.03	2.49	2.31	2.90	9.18	4.69
SE	0.09	0.12	0.71	0.00	1.45	0.07	0.11	0.31	0.84	0.45	0.21	0.14	0.30	2.36	3.17
n	25	26	2	1	3	51	51	3	6	5	7	7	2	7	5
Mn (mg L⁻¹)															
mean	0.04	0.06	0.21	0.05	0.19	0.07	0.06	0.14	0.10	0.16	0.20	0.17	0.42	0.13	0.41
SE	0.00	0.01	0.06	0.00	0.08	0.01	0.01	0.06	0.02	0.04	0.03	0.02	0.16	0.02	0.25
n	25	26	2	1	3	51	51	3	6	5	7	7	2	7	5

<u>Ca (mg L⁻¹)</u>															
mean	4.18	4.59	12.50	0.72	9.60	4.43	4.56	6.48	2.73	9.83	5.42	5.43	36.80	0.98	22.19
SE	0.28	0.21	6.71	0.00	5.13	0.12	0.16	4.96	1.79	3.59	0.69	0.68	0.00	0.14	5.77
n	25	26	2	1	3	51	51	3	6	5	7	7	2	7	5
<u>Mg (mg L⁻¹)</u>															
mean	0.71	0.79	2.10	0.32	1.68	0.82	0.84	1.03	0.66	1.56	0.82	0.84	6.15	0.46	4.12
SE	0.04	0.03	1.10	0.00	0.85	0.01	0.02	0.55	0.23	0.45	0.09	0.09	0.16	0.06	1.08
n	25	26	2	1	3	51	51	3	6	5	7	7	2	7	5
<u>Na (mg L⁻¹)</u>															
mean	0.23	0.27	0.66	0.09	0.48	0.23	0.30	0.32	0.12	0.36	0.44	0.42	0.70	0.28	0.48
SE	0.02	0.01	0.34	0.00	0.20	0.01	0.07	0.24	0.07	0.12	0.05	0.03	0.01	0.23	0.06
n	25	26	2	1	3	51	51	3	6	5	7	7	2	7	5
<u>K (mg L⁻¹)</u>															
mean	0.15	0.17	0.30	0.14	0.28	0.02	0.07	0.08	0.03	0.08	0.04	0.09	0.73	0.16	0.18
SE	0.01	0.01	0.04	0.00	0.05	0.01	0.04	0.07	0.02	0.03	0.01	0.03	0.65	0.11	0.04
n	25	26	2	1	3	51	51	3	6	5	7	7	2	7	5
<u>SO₄ (uM)</u>															
mean	1.38	1.79	6.25	0.46	6.20	1.66	8.30	4.49	0.53	3.14	30.15	27.40	16.53	11.01	13.88
SE	0.54	0.40	2.67	0.00	2.64	0.29	5.90	4.10	0.22	1.31	6.13	7.57	14.66	5.26	5.33
n	25	27	4	3	4	50	50	3	6	6	7	7	2	6	5
<u>Cl (uM)</u>															
mean	42.3	48.6	5.5	7.8	37.9	39.3	40.7	2.1	3.7	6.5	1.5	0.9	0.4	0.3	2.2
SE	4.3	7.0	2.0	0.0	32.2	3.3	5.7	0.9	3.0	5.3	1.1	0.4	0.3	0.1	1.1
n	25	27	4	3	4	50	50	2	5	5	7	7	2	6	5
<u>S (mg L⁻¹)</u>															
mean	0.18	0.23	0.58	0.04	0.52	0.20	0.21	0.30	0.14	0.37	0.16	0.14	0.52	0.02	0.36
SE	0.01	0.01	0.22	0.00	0.19	0.00	0.01	0.17	0.07	0.11	0.01	0.01	0.10	0.01	0.05
n	25	26	2	1	3	51	51	3	6	5	7	7	2	7	5
<u>TSS (mg L⁻¹)</u>															
mean	3.5	6.7	62.2	32.5	43.0	2.9	3.9	805.7	17.0	7.0	3.8	3.5	6.3	19.5	24.8
SE	0.3	0.8	13.3	18.2	10.9	0.3	0.4	797.0	10.6	1.5	1.0	1.2	0.3	15.1	13.5
n	40	40	3	4	5	43	43	3	4	6	6	6	2	5	3

Table 7

Epilithic chlorophyll-a, standing stocks and molar ratios of epilithic carbon, nitrogen and phosphorus from rocks in the Reference and thermokarst-Impacted reaches of Toolik River. Means, sample size (n = single rock scrub), and 1 standard error (SE) are reported. The significance of differences between stream samples taken along the Reference and Impacted reaches were tested with a t-test and values in bold with ^a following the mean indicate significantly higher means at the $\alpha = 0.05$ level

		Chlorophyll-a ($\mu\text{g}/\text{cm}^2$)	Standing Stocks ($\mu\text{mol}/\text{cm}^2$)			Molar Ratios		
Riffle Rocks			Carbon	Nitrogen	Phosphorus	C:N	C:P	N:P
2009	Reference	0.60 (0.10)	57.9 (8.9)	3.75 (0.51)	0.04 (0.01)	15.6^a (0.5)	2261 (561)	146 (37)
	Impacted	1.11^a (0.15)	55.8 (7.6)	5.45^a (0.77)	0.03 (0.004)	11.5 (1.7)	1894 (358)	185 (27)
	<i>n</i>	16	16	16	15	14-16	14-15	14-15
2010	Reference	0.38 (0.10)	60.5 (15.6)	6.78 (2.27)	0.06 (0.01)	10.3 (1.2)	1183 (408)	112 (29)
	Impacted	0.35 (0.08)	71.4 (15.4)	4.99 (1.02)	0.06 (0.02)	14.3^a (0.3)	1561 (248)	108 (16)
	<i>n</i>	12	11	11	12	11	11	11
2011	Reference	0.66 (0.07)	132 (21)	8.50 (1.29)	0.07 (0.008)	15.3 (0.4)	2213 (510)	141 (30)
	Impacted	1.16^a (0.19)	168 (15)	13.2 (3.2)	0.06 (0.005)	15.3 (0.9)	2876 (391)	213 (41)
	<i>n</i>	16	15-16	15-16	16	15-16	15	15

Table 8

Global R values reported below from the comparisons between sampling locations in the ANOSIM. We considered any $R > 0.5$ to be ecologically significant. Overall $R = 0.3786$.

	M2	M3	T1	T2
M3	0.08	-	-	-
T1	0.92	0.91	-	-
T2	0.78	0.75	0.51	-
T3	0.62	0.58	0.19	0.34

Table 9

Water chemistry variables included in the vector analysis with sample size (N), the correlation between the vector and NMS ordination grouping, and associated probability (P-value) reported

Variable	N	Correlation	P-value
Alkalinity	147	0.54	<0.001
DOC	147	0.82	<0.001
NH ₄ ⁺	121	0.50	<0.001
PO ₄ ⁻	128	0.17	0.180
NO ₃ ⁻	100	0.39	0.005
TDN	147	0.84	<0.001
TDP	144	0.36	<0.001
Ca ⁺	147	0.74	<0.001
K ⁺	129	0.43	0.001
Mg ⁺	147	0.71	<0.001
Na ⁺	144	0.81	<0.001
Al ⁻	145	0.77	0.012
Fe ⁺	147	0.67	<0.001
Mn ⁻	147	0.64	<0.001
S	146	0.62	<0.001
SO ₄ ⁻	145	0.59	<0.001
Cl ⁻	143	0.61	<0.001
TSS	93	0.51	<0.001

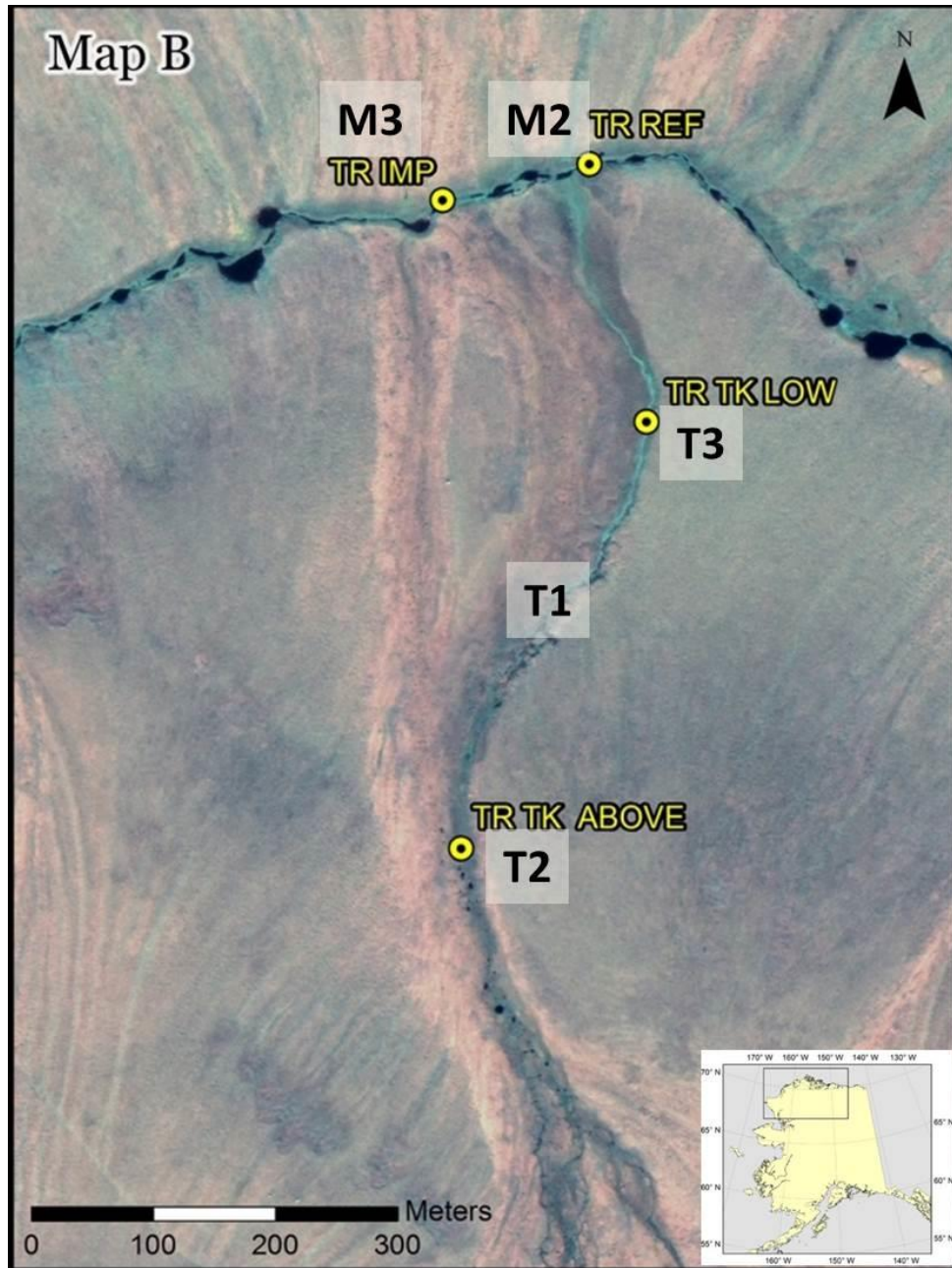


Figure 1. Toolik River study site sampled 2009-2011. Map Credit: R. Fulweber, Toolik Field Station GIS and Remote Sensing Facility.



Figure 2. Ground-level site photos at Toolik River gully and main channel from 2009, approximately 5 years after formation. Top left: The southern edge of the gully headwall (high up in the feature above the T1 sampling location); top right: tunnel inside gully feature; bottom left: turbid outflow from hillslope at the confluence of the lower gully/water track tributary (T3) with the Toolik River; bottom right: view facing upstream at the reference reach from confluence with the gully/water track tributary entering the stream on the true left bank (in between M2 and M3).

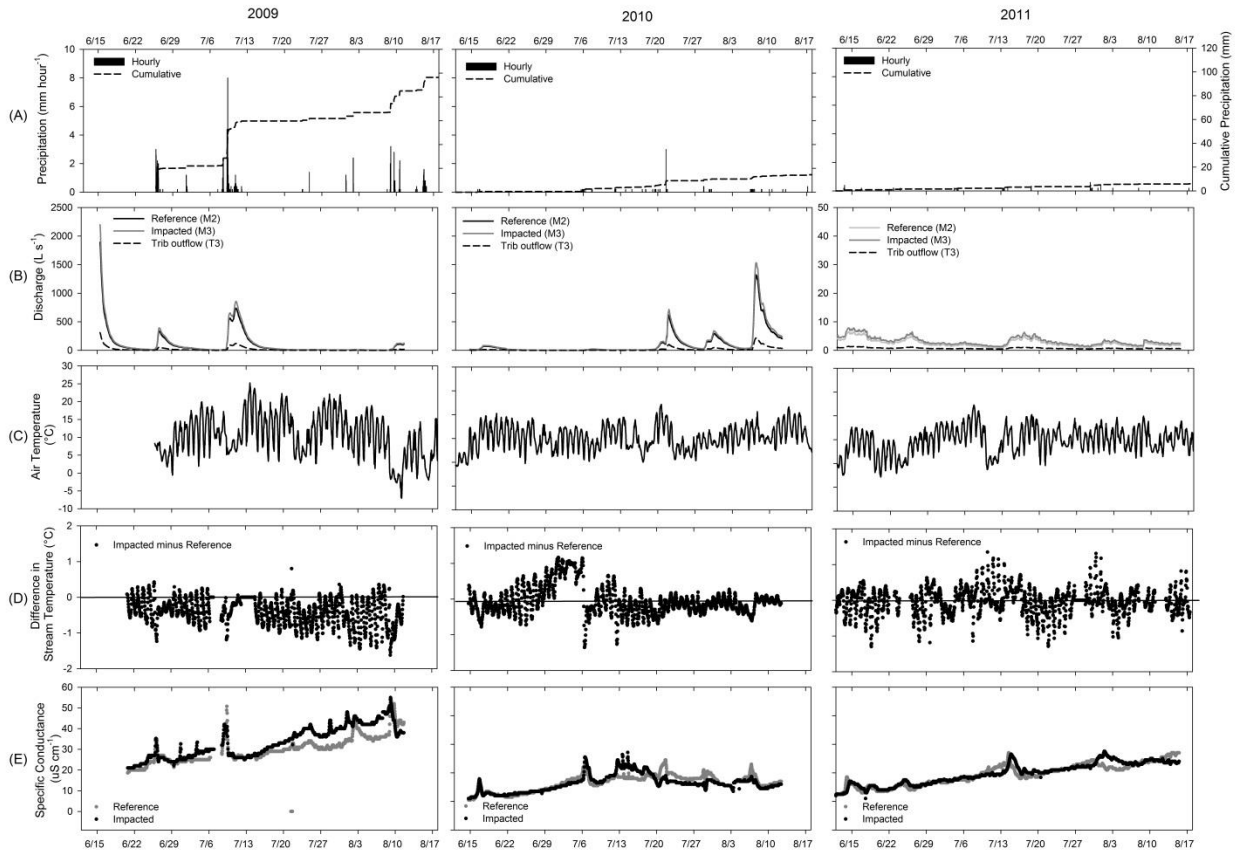


Figure 3. Hydrometeorological conditions in the Reference and Impacted reaches of Toolik River in 2009-2011. (A) Hourly precipitation from weather station located on hillslope adjacent to thermokarst gully feature. (B) Hourly stream discharge (note change of scale for 2011). (C) Hourly air temperature from weather station. (D) Difference between Impacted and Reference hourly stream temperatures from HOBO level loggers (except for 2009 Impacted reach where YSI sonde data were used). (E) Specific conductance from YSI sondes.

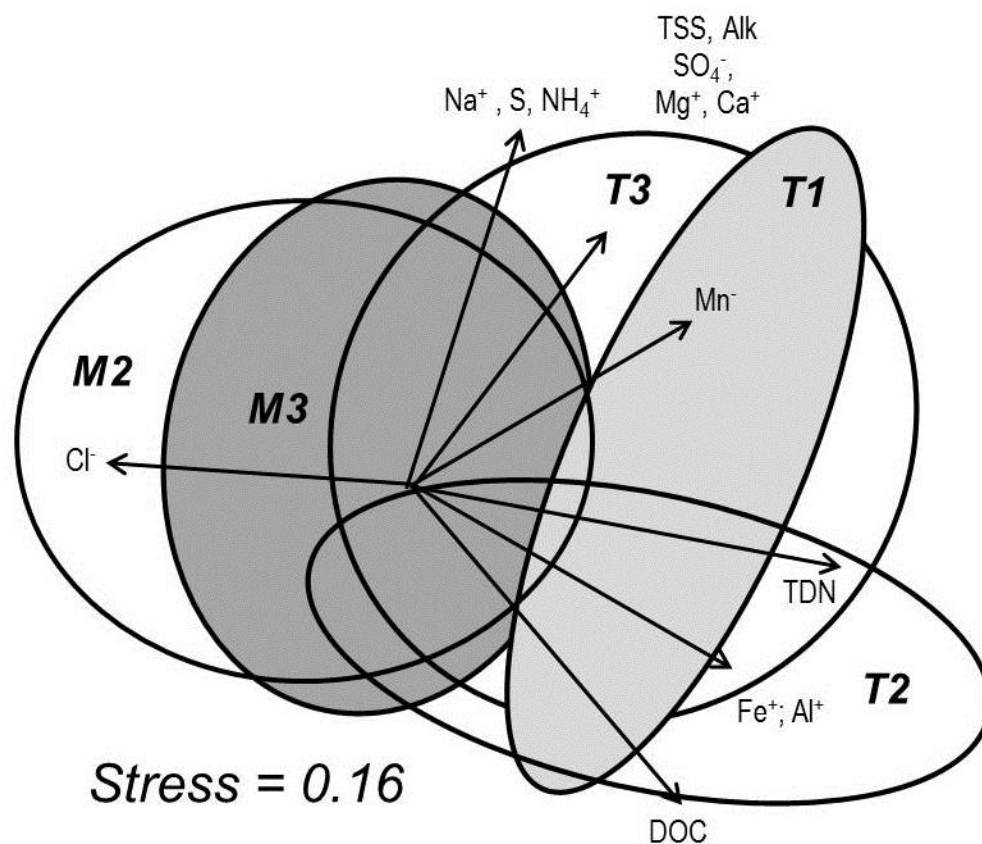


Figure 4. Non-metric multidimensional scaling (NMS) ordination of water chemistry data from 5 sampling locations (T1; T2; T3; T4; T5 in bold italics) grouped by the three study years (2009-2011) based on pairwise similarity estimates (Bray-Curtis). Water chemistry variables included are: alkalinity; DOC; NH₄⁺; PO₄⁺; NO₃⁻; TDN; TDP; Ca⁺; K⁺; Mg⁺; Na⁺; Fe⁺; Mn⁺; S; SO₄⁻; and Cl⁻. The overlaid vectors indicate the strength of correlation between water chemistry variables and the clusters within multidimensional space.

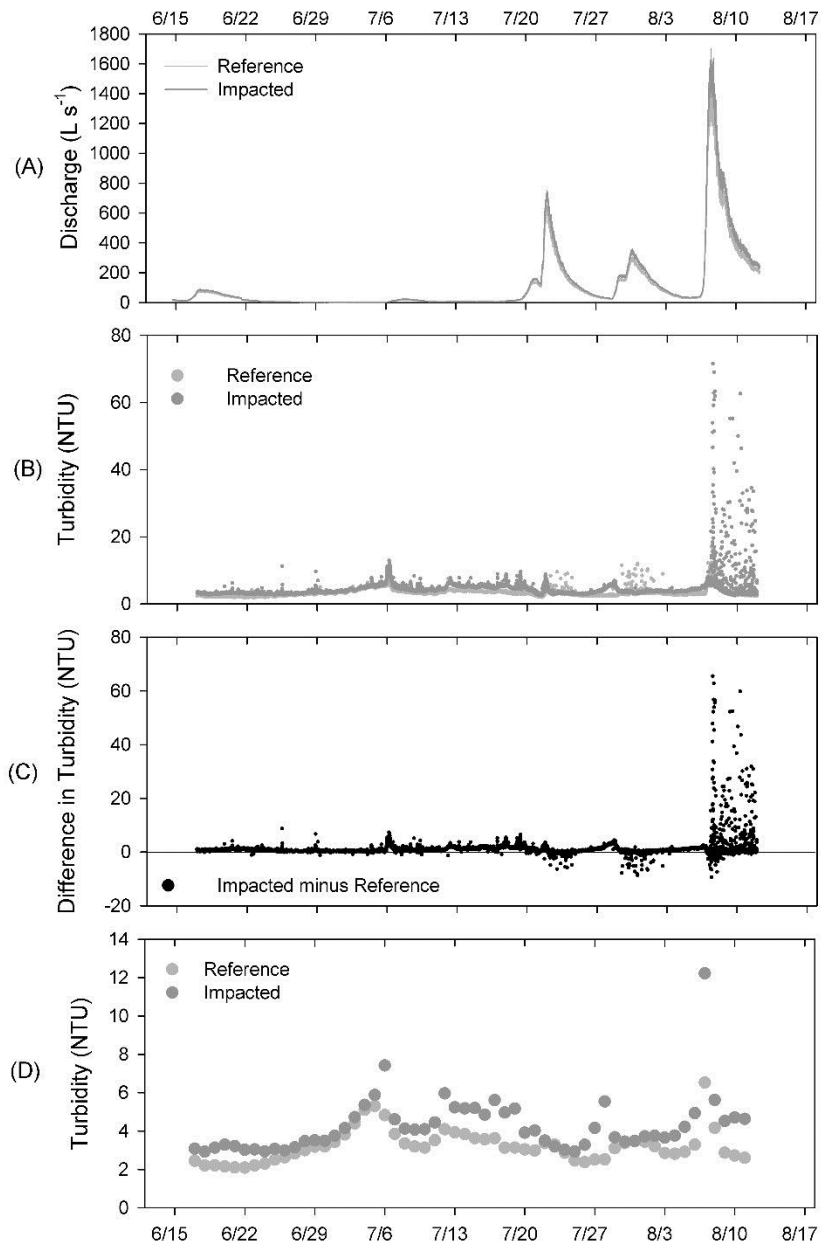


Figure 5. Continuous records of A) 5-minute discharge, B) 5-minute turbidity, C) difference in turbidity, and D) mean daily turbidity for the Toolik River Reference and Impacted reaches during the 2010 summer season.

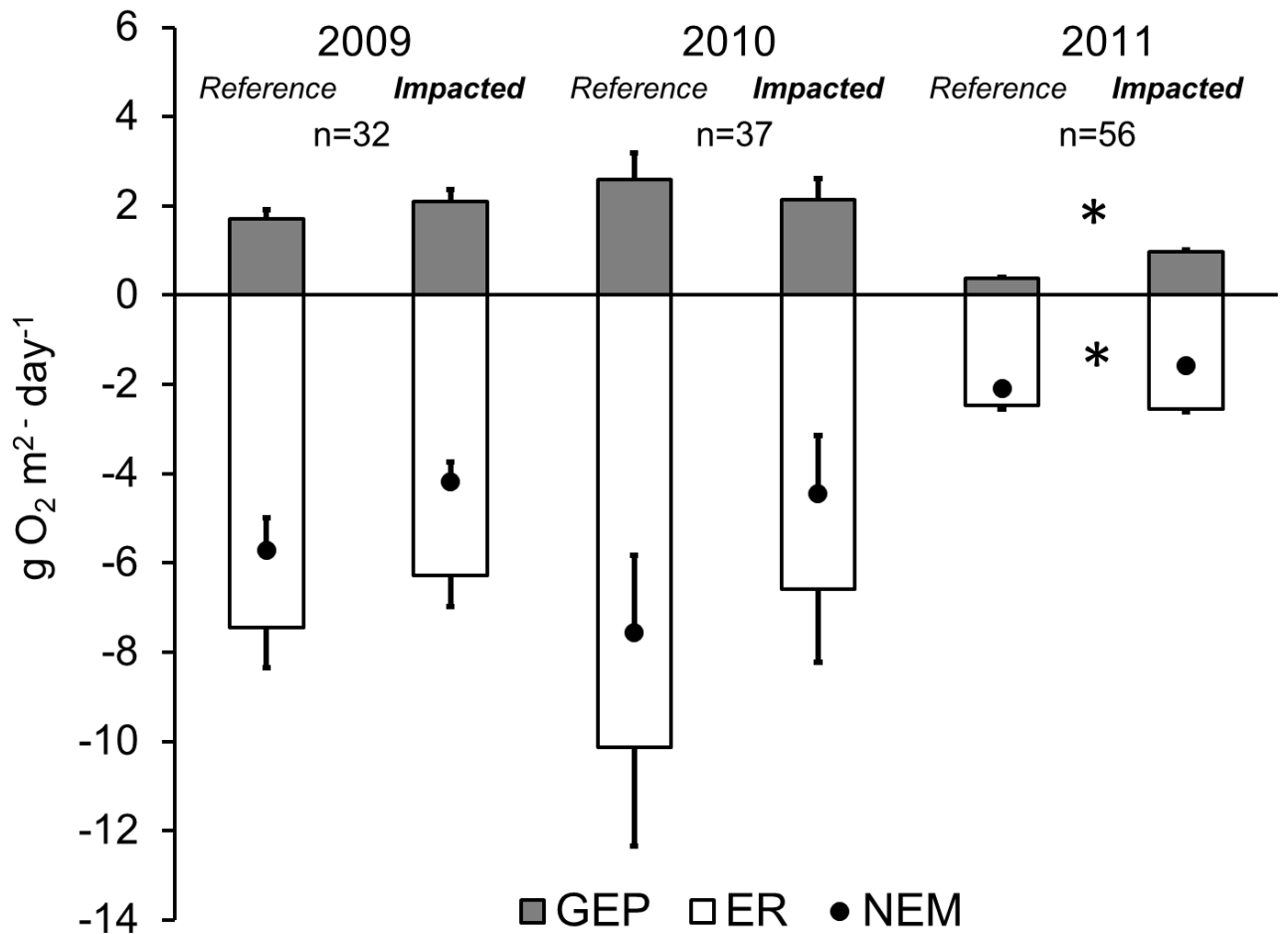


Figure 6. Seasonal mean and standard error of whole-stream metabolism metrics: gross ecosystem productivity (GEP), community respiration (CR), and net ecosystem productivity (NEP) of baseflow days for Toolik River Reference and Impacted reaches. Sample sizes for 2009-2011 are 32, 32, and, 53 days, respectively. ‘*’ indicates significant differences (P<0.001).

**CHAPTER 4. THE ROLE OF WATERSHED CHARACTERISTICS,
PERMAFROST THAW, AND WILDFIRE ON DISSOLVED
ORGANIC CARBON BIODEGRADABILITY AND WATER
CHEMISTRY IN ARCTIC HEADWATER STREAMS**

Title

The role of watershed characteristics, permafrost thaw, and wildfire on dissolved organic carbon biodegradability and water chemistry in Arctic headwater streams

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Abstract

In the Alaskan Arctic, rapid climate change is increasing the frequency of disturbance including wildfire and permafrost collapse. These pulse disturbances may influence the delivery of dissolved organic carbon (DOC) to aquatic ecosystems, however the magnitude of these effects compared to the natural background variability of DOC at the watershed scale is not well known. We measured DOC quantity, composition, and biodegradability from 14 river and stream reaches (watershed sizes ranging from 1.5-167 km²) some of which were impacted by permafrost collapse (thermokarst) and fire. We found that region had a significant impact on quantity and biodegradability of DOC, likely driven by landscape and watershed characteristics such as lithology, soil and vegetation type, elevation, and glacial age. However, contrary to our hypothesis, we found that streams disturbed by thermokarst and fire did not contain significantly altered labile DOC fractions compared to adjacent reference waters, potentially due to rapid ecosystem recovery after fire and thermokarst, as well as the limited spatial extent of thermokarst. Overall, biodegradable DOC ranged from 4 to 46% and contrary to patterns of DOC biodegradability in large Arctic rivers, seasonal variation in DOC biodegradability showed no clear pattern between sites, potentially related to stream geomorphology and position along the river network. While thermokarst and fire can alter DOC quantity and biodegradability at the scale of the feature, we conclude that tundra ecosystems are resilient to these types of disturbance.

Keywords

Permafrost, DOC, dissolved organic carbon, biolability, biodegradability, Arctic rivers, Arctic streams, Arctic tundra, wildfire, fire, disturbance, thermokarst, thermo-erosion, thermo-erosion gully, retrogressive thaw slump

1. Introduction

As the Arctic warms, the biogeochemical signature of its rivers and streams will likely be an indicator of the response of aquatic and adjacent terrestrial ecosystems to climate change (Frey and McClelland, 2009; Holmes et al., 2000; McClelland et al., 2007). Arctic freshwater ecosystems process and transport substantial loads of dissolved organic carbon (DOC) delivering 34-38 Tg yr⁻¹ to the Arctic Ocean, and mineralizing or immobilizing another 37-84 Tg yr⁻¹ (Holmes et al., 2012; McGuire et al., 2009).

Biodegradable DOC (BDOC) is the reactive DOC fraction and is defined as the percent DOC loss over time (typically 7 to 40 days) due to mineralization, uptake, or sorption (McDowell et al., 2006). Given anticipated changes in the arctic climate, there has been growing interest to quantify changes in the magnitude of overall DOC flux (Holmes et al., 2012; Tank et al., 2012), as well as the BDOC exported by small headwater streams and large rivers in the Arctic (O'Donnell et al., 2012; Spencer et al., 2008; Striegl et al., 2005; Tank et al.), particularly in areas impacted by disturbances associated with climate change.

Disturbance regimes in arctic and boreal ecosystems have the potential to escalate in response to future changes in climate. Examples of physical responses to climate

change in northern Alaska include the deepening of active layer thickness (Shiklomanov et al., 2010), permafrost warming (Romanovsky et al., 2002; Romanovsky et al., 2011), thermokarst formation (Balser et al., 2014; Belshe et al., 2013; Jorgenson et al., 2006), and wildfire (Randerson et al., 2006). There is evidence of recent increase in thermokarst formation (Balser et al., 2014; Gooseff et al., 2009) on the North Slope of Alaska and wildfire has the potential to become a major disturbance factor in the tundra region (Higuera et al., 2011).

Thaw of ice-rich permafrost results in soil collapse or subsidence, termed thermokarst (Jorgenson et al., 2008). Thermokarst can export substantial quantities of sediment, carbon, nitrogen, and phosphorus to receiving waters (Bowden et al., 2008; Dugan et al., 2012; Harms et al., 2014; Kokelj et al., 2005; Kokelj et al., 2013; Kokelj et al., 2009; Lamoureux and Lafrenière, 2009; Lewis et al., 2011; Malone et al., 2013). The magnitude of exported material depends largely on thermokarst size, type, activity, and hydrologic connectivity (Abbott et al., 2014; Lafrenière and Lamoureux, 2013; Lewis et al., 2011). For example, thermokarst features can mobilize substantial amount of sediments and nutrients which are not delivered to downslope aquatic ecosystems and instead retained along the hillslopes or in the riparian zone. Recent work has shown that DOC in the outflow of thermokarst features is highly labile (Abbott et al.; Vonk et al., 2013; Woods et al., 2011), particularly when exposed to light (Cory et al., 2013). While sediment and solute concentrations and the proportion of BDOC can be high in thermokarst outflow, the impact on the catchment depends on the total mass flux or load (Lewis et al., 2011). The effects of thermokarst disturbance on arctic aquatic ecosystems

are poorly understood at the watershed scale, limiting useful inferences about future system response to climate change.

The Anaktuvuk River Fire, the largest fire on record for the North Slope of Alaska, burned 1,039 km² in 2007 and removed ~ 31 % of tundra ecosystem carbon (Mack et al., 2011). The organic horizon of tundra soils insulates permafrost from warm summer air temperatures and the removal of surface soil carbon promotes underlying permafrost degradation (Burn, 1998; Yoshikawa et al., 2002), potentially triggering thermokarst development (Osterkamp and Romanovsky, 1999). Wildfire disturbance in lower latitude ecosystems has been shown to increase concentrations of major ions and nutrients in soil and stream water (Bayley et al., 1992a; Bayley et al., 1992b; Chorover et al., 1994). In the boreal forest of Alaska, stream DOC concentration declined following a wildfire, presumably due to loss of microbial biomass (Betts and Jones, 2009; Petrone et al., 2007; Schindler et al., 1997) and with a lower proportion of bioavailable dissolved organic matter as carbon degrades to more recalcitrant forms post-fire and during thermokarst formation (Balcarczyk et al., 2009).

Across various biomes, the composition and biodegradability of riverine DOC changes seasonally due to a tight coupling between terrestrial and aquatic ecosystems (Fellman, Hood, Edwards, and D'Amore, 2009; Holmes et al., 2008; Wang, Ma, Li, Song, and Wu, 2012). In the Arctic, the quantity and quality of DOC is highest during snowmelt and decreases progressively through the summer (Holmes et al.; Mann et al., 2012; Vonk et al., 2013). However, the majority of studies investigating arctic BDOC have focused on downstream reaches in large alluvial systems; the seasonal and spatial

variation of BDOC in headwater streams is largely unknown. Thus, it is difficult to assess the degree to which DOC might be processed during transport from headwaters to higher order reaches.

The questions we address in this paper are, “Does BDOC and water chemistry differ at the watershed scale among landscape types?” and “Does BDOC and water chemistry differ in streams impacted by thermokarst and fire?” To answer these questions we measured the quantity, biodegradability, and aromaticity of DOC and background water chemistry from arctic headwater streams and rivers. We sampled watersheds in three geographic regions affected by a combination of fire and thermokarst to evaluate controls on DOC quantity and biodegradability at the watershed scale. We hypothesized thermokarst would increase DOC concentrations and BDOC due to the delivery of labile carbon from thawed permafrost. Because wildfire in the Arctic can directly impact DOC export, as well as have secondary effects due to changes in active layer depth and extent of permafrost, we hypothesized that wildfire may decrease BDOC due to the combustion of soil carbon stocks during fire. However, if wildfire promotes extensive permafrost degradation and thermokarst production then BDOC concentrations might increase.

2. Methods

2.1. Study areas and sampling design

We took advantage of natural disturbance to test our hypotheses. We collected stream water from 16 reaches, 11 of which were individual arctic rivers and streams on or near the North Slope of Alaska including the regions around the Toolik Field Station, Feniak Lake, and the Anaktuvuk River wildfire area (Fig. 1, Table 1). Seven of the

stream sites were apparently undisturbed (reference) reaches and nine sites were impacted by a combination of wild fire and thermokarst of various types, including retrogressive thaw slumps and active layer detachment slides, two of the most common thermokarst morphologies in upland landscapes (Kokelj and Jorgenson, 2013). The Toolik Field Station is located 254 km north of the Arctic Circle and 180 km south of the Arctic Ocean. The average annual temperature is -10°C and average monthly temperatures range from -25°C in January to 11.5°C in July. The Toolik area receives 320 mm of precipitation annually with 200 mm falling between June and August (Center, 2011). Feniak Lake is located 360 km west of the Toolik Field Station in the central Brooks Range in the Noatak National Preserve. The Feniak region receives more precipitation than Toolik and Anaktuvuk with an annual average of 450 mm (WRCC, 2011). In the summer of 2007 in the Anaktuvuk River wildfire area, above-normal temperatures, below-normal precipitation, and extremely low soil moisture conditions favored fire conditions when a lightning strike ignited the tundra on 16 July 2007. Air temperatures in July to September 2007 were their warmest over a 129-year record, with a $+2.0^{\circ}\text{C}$ anomaly (Jones et al., 2009). The Anaktuvuk area receives the bulk of its precipitation during the months of June through September and the summer of 2007 was the driest of a 29 year record (1979-2007), with the four month total precipitation being just over 20 mm, compared to the long-term normal of 107 mm (Jones et al., 2009). All three areas are underlain by continuous permafrost. Landscapes in the Toolik and Feniak Lake area are underlain by glacial till, bedrock and loess parent materials ranging in age from 10-400 ka (Hamilton, 2003). The two sites sampled in the Toolik area consist

primarily of glacial deposits assigned to the Sagavanirktok River (middle Pleistocene) and Itkillik I and II (late Pleistocene) glaciations of the central Brooks Range (Hamilton, 2003). Upland substrates in the Feniak area include non-carbonate, carbonate and ultramafic lithologies (Jorgenson et al., 2001), and are typically overlain by colluvial deposits, soliflucted hillslopes, glacial till and outwash primarily of early Itkillik Age (roughly 50,000 years BP) (Hamilton, 2009). The Anaktuvuk River area is on a substantially older (> 700 ka) landscape farther north from the field station and foothills. The southern one-third portion of the burned area rests on a combination of upland colluvium or old glacial surfaces while the northern two-thirds of the burn surface rests on eolian silt deposited in the mid-Pleistocene (Jorgenson et al., 2010).

2.2. Sample collection

In 2011, we sampled reference streams and streams impacted by thermokarst and wildfire near the Toolik Field Station, the Anaktuvuk burn scar, and Feniak Lake. In the Toolik area we sampled the Kuparuk River (Site 1) and Oksrukyuk Creek (Site 2), both of which have not been impacted by fire or thermokarst. In the Anaktuvuk area, we sampled four reference rivers on 6 August 2011, two of which we analyzed for BDOC (Burn Reference 1 = Site 3 and Burn Reference 2 = Site 4), located to the east of the burn boundary to serve as landscape references for the sites located within the burned scar. Within the Anaktuvuk burned boundary we sampled four unique streams including the South (Site 5) and North (Site 6) Rivers, both of which were burned, but undisturbed by thermokarst. Also within the Anaktuvuk scar, we sampled two watersheds referred to as the Valley of Thermokarst; one watershed (Sites 7a and 7b) that was burned but had no

thermokarst features present and one watershed (Sites 8a and 8b) was burned and contained numerous active layer detachment slides that formed on the south-facing slope post-fire. In the Feniak area we focused our efforts at two sites. We sampled a small watershed containing two tributaries, Bloodslide Reference (Site 9) that drained the northwestern portion of the watershed unimpacted by thermokarst and Bloodslide Impacted (Site 10) that drained the southeastern side of the watershed and received the outflow of a very recent, active layer detachment slide. The other location in Feniak was along a larger headwater system impacted by three large, active thaw slumps and we sampled upstream and downstream of both the first (Sites 11a and 11b) and third (Sites 12a and 12b) thaw slump features.

To quantify seasonal variability of BDOC we took repeat measurements four to five times over the 2011 summer season from the Toolik and Anaktuvuk stream sites, except for the two Anaktuvuk reference sites that were sampled once. Due to their remote locations, sites located in the Feniak Lake area were sampled once during 2011. At each stream site, we collected four replicate field samples, which we filtered (0.7 μm , Advantec GF-75) into 250 ml amber LDPE bottles for transport to Toolik Field Station or Feniak Lake base camp and set up incubations within 24 hours of collection. We also collected separate bottles for background water chemistry (filtered and preserved for later analyses) and for photometric absorbance analyses (filtered and measured within 24 hours, except for the Feniak samples which were measured within a week back at Toolik Field Station).

2.3. BDOC incubation assays

We followed the BDOC incubation protocol described in Abbott et al. (2014). In brief, we amended all samples with nutrients (state the types and concentrations), inoculated them with a common bacterial community from the local site, and measured DOC loss at three time steps: initial DOC at day 0 (t_0), at day 10 (t_{10}), and at the end of a 40 day incubation (t_{40}), we found that the day 10 incubations yielded inconsistent results (i.e., DOC gain at t_{10} yielding negative BDOC) and so for the purposes of this paper we focus only on DOC loss over 40 days (t_{40}). DOC loss (absolute loss and percentage loss relative to initial concentration) was calculated for each field replicate sample ($n=4$) on each sampling date. Mean values for initial DOC concentration (μm); absolute 40-day loss (μm); and 40-day percent loss (%) were calculated from the four field replicates for each site and date. Quality control of the calculations was evaluated on a case by case basis and any sample where a suspicious DOC measurement was identified was removed. Only one replicate out of the total of 184 samples was removed.

2.4. DOC composition (SUVA₂₅₄)

We characterized DOC composition by Specific Ultraviolet Absorbance at 254 nm (SUVA₂₅₄; $\text{L mg C}^{-1} \text{ m}^{-1}$), a photometric measure of DOC aromaticity (Weishaar et al., 2003). UV absorbance was measured on a Shimadzu UV-1601 using a 1.0 cm quartz cell and was calculated by dividing UV absorbance by DOC concentration in mg/L.

2.5. Water chemistry

We analyzed water samples for total suspended sediment (TSS, mg L^{-1}); alkalinity ($\mu\text{eq L}^{-1}$); total dissolved nitrogen (TDN, μM); ammonium (NH_4^+ , μM); nitrate (NO_3^- ,

μM); total dissolved phosphorus (TDP, μM); soluble reactive phosphorus as phosphate (PO_4^{3-} , μM); and cations (magnesium, Mg^+ ; calcium, Ca^+ ; potassium, K^+ ; sodium, Na^+ , mg L^{-1}). Supplementary Table A1 summarizes the methods and instruments used for water chemistry analyses. The sites in the Anaktuvuk and Toolik areas were sampled with ISCO automated samplers deployed for daily composite sampling (except for Sites 7b and 8b which were sampled manually). Sites in the Feniak area were sampled manually.

2.6. Statistics

For all analyses, we evaluated normality with normal probability plots and equal variance with Levene's test (Levene, 1960). The variance values around all mean values reported below are standard errors (SE). We tested for differences in BDOC metrics and background water chemistry variables among streams within groups defined *a priori* by analysis of variance (ANOVA). Significant differences between streams ($p < 0.05$) were further evaluated using Tukey's multiple-comparison test (Lane, 2010). We considered comparisons with a p value < 0.1 to be marginally significant. If the Levene unequal variances test was significant, Welch's test (Welch, 1951) was used to detect differences instead of ANOVA. Normality plots, equal variance tests and ANOVA analyses were performed with JMP Pro version 11.0 (SAS Institute Inc., 2012). Linear regression was used to determine correlations between SUVA and BDOC %, and also to determine relationships between BDOC % and date for those sites that were measured repeatedly. Linear regression analyses were performed with SigmaPlot version 11.0 (Systat Software, Inc., San Jose California, USA).

3. Results

3.1 Initial (t_0) DOC concentrations

Anaktuvuk reference sites had higher initial DOC concentrations ($977 \pm 103 \mu\text{M}$, $n=2$) than Feniak ($316 \pm 83.9 \mu\text{M}$, $n=3$, $P < 0.001$) and Toolik ($259 \pm 46.0 \mu\text{M}$, $n=10$, $P < 0.0001$) reference sites (Fig. 2A). The comparison of the reference and thermokarst-impacted sites in Feniak revealed no significant effect on initial DOC ($P=0.96$) (Fig. 3A, left). Moreover, we found no influence of thermokarst on initial DOC ($P=0.92$) by comparing the adjacent Reference and Impacted Valley of Thermokarst catchments [Sites 7a and 7b and 8b (burned) versus 8a (burned + thermokarst)] (Fig. 3A, right). Combining all sites in a region together, the initial DOC concentration in the Anaktuvuk region ($1098 \pm 38.4 \mu\text{M}$, $n=30$) was more than three times greater than in the Feniak region ($312 \pm 85.5 \mu\text{M}$, $n=6$, $P < 0.0001$) and in the Toolik region ($259 \pm 66.4 \mu\text{M}$, $n=10$, $P < 0.0001$) streams (Fig. 4A).

3.2 BDOC

The absolute BDOC concentration in Reference Feniak streams ($125.2 \pm 17.0 \mu\text{M}$, $n=3$, $P < 0.01$) and reference Anaktuvuk streams ($125.0 \pm 20.8 \mu\text{M}$, $n=2$, $P < 0.05$) was greater than Toolik reference sites ($45.5 \pm 9.3 \mu\text{M}$, $n=10$) (Fig. 2B). Feniak reference sites contained the highest BDOC % ($38.1 \pm 2.6 \%$, $n=3$) compared to Toolik ($18.5 \pm 1.4 \%$, $n=10$, $P < 0.0001$) and Anaktuvuk ($14.5 \pm 3.2 \%$, $n=30$, $P < 0.001$) reference sites (Fig. 2C). There was no significant effect of thermokarst inflow on absolute BDOC ($P=0.91$) or BDOC % ($P=0.99$) (Fig. 3B-C, left). Nor did we find an effect of thermokarst on absolute BDOC ($P=0.83$) or BDOC % ($P=0.71$) in the Valley of Thermokarst [Sites 7a and 7b and

8b (burned) versus 8a (burned + thermokarst)] (Fig. 3B-C, right). Combining all sites within a region, we found that the absolute BDOC (Fig. 4B) was significantly lower in the Toolik region ($45 \pm 15.1 \mu\text{M}$, $n=10$) compared to the Feniak region ($123 \pm 19.5 \mu\text{M}$, $n=6$, $P < 0.01$) and the Anaktuvuk region ($105 \pm 8.7 \mu\text{M}$, $n=30$, $P < 0.01$) streams. BDOC % (Fig. 4C) was significantly different ($P < 0.0001$) among streams from all three regions: Feniak ($38.1 \pm 1.8 \%$, $n=6$); Toolik ($18.5 \pm 1.4 \%$, $n=10$); and Anaktuvuk ($9.6 \pm 0.8 \%$, $n=2$).

3.3 SUVA₂₅₄

The values of SUVA₂₅₄ ranged from 1.31 to 6.87 L mg C⁻¹ m⁻¹ across all streams sampled. The SUVA₂₅₄ values for the Anaktuvuk reference sites (4.2 ± 1.7 L mg C⁻¹ m⁻¹, $n=2$) were significantly higher than the values from the Feniak reference sites (1.8 ± 0.4 L mg C⁻¹ m⁻¹, $n=3$, $P=0.01$) or the Toolik reference sites (2.1 ± 0.1 L mg C⁻¹ m⁻¹, $n=10$, $P=0.01$) reference sites (Fig. 2D). Thermokarst inflow had no significant impact on SUVA₂₅₄ in the Feniak sites ($P=0.79$, Fig. 3D, left). We also found no influence of thermokarst on SUVA₂₅₄ ($P=0.66$) within the Valley of Thermokarst burned catchments [Sites 7a and 7b and 8b (burned) versus 8a (burned + thermokarst)] (Fig. 4D, right). Combining all sites within a region, the SUVA₂₅₄ measurements differed significantly by region ($P < 0.0001$). Toolik and Feniak area streams had lower SUVA₂₅₄ values (range 1.31 - 2.62 L mg C⁻¹ m⁻¹), indicative of low humic content and aromaticity, compared to streams in the Anaktuvuk area (range 2.57 - 6.87 L mg C⁻¹ m⁻¹). SUVA₂₅₄ values from Anaktuvuk sites (4.8 ± 0.12 L mg C⁻¹ m⁻¹, $n=30$) were more than double those in Feniak (1.9 ± 0.29 L mg C⁻¹ m⁻¹, $n=6$, $P < 0.0001$) and Toolik (2.1 ± 0.22 L mg C⁻¹ m⁻¹, $n=10$,

$P < 0.0001$) streams (Fig. 4D). We found a negative exponential relationship between $SUVA_{254}$ and BDOC % (Fig. 5).

3.4. Background water chemistry

Most background water chemistry variables differed significantly among regions (Fig. 6). Stream alkalinity was approximately five-fold higher in the Feniak streams ($1734 \pm 1167 \mu\text{eq L}^{-1}$, $n=40$) compared to alkalinity in Toolik ($310 \pm 69 \mu\text{eq L}^{-1}$, $n=74$, $P < 0.0001$) and Anaktuvuk ($361 \pm 287 \mu\text{eq L}^{-1}$, $n=168$, $P < 0.0001$) streams. Anaktuvuk streams contained approximately three times the amount of TDN and TDP compared to Feniak and Toolik streams ($P < 0.0001$). Ammonium (NH_4^+) concentrations in the Feniak streams were variable, but two of the sites contained particularly high concentrations. Nitrate (NO_3^-) was significantly different ($P < 0.0001$) across all three regions with Toolik having the highest concentrations ($5.57 \pm 1.65 \mu\text{M}$, $n=74$), followed by Feniak ($3.64 \pm 3.56 \mu\text{M}$, $n=40$) and Anaktuvuk ($0.26 \pm 0.81 \mu\text{M}$, $n=168$). No significant differences were found across regions for phosphate (PO_4^{3-}).

We compared background water chemistry between the Anaktuvuk reference sites (from the opportunistic sampling on August 6, 2011) and burned sites using data only from that date (data not shown). We found that NH_4^+ (Reference $0.15 \pm 0.12 \mu\text{M}$, $n=4$, versus Burn $0.63 \pm 0.11 \mu\text{M}$, $n=5$, $P=0.02$), PO_4^{3-} (Reference $0.06 \pm 0.04 \mu\text{M}$, $n=4$, versus Burn $0.26 \pm 0.04 \mu\text{M}$, $n=5$, $P=0.01$), and TDP (Reference $0.10 \pm 0.10 \mu\text{M}$, $n=4$, vs. Burn $0.49 \pm 0.06 \mu\text{M}$, $n=8$, $P=0.01$) were all significantly higher in the burned streams compared to the reference streams on that date. Background DOC was marginally higher (Reference $915 \pm 174 \mu\text{M}$, $n=4$, versus Burn mean $1341 \pm 123 \mu\text{M}$, $n=8$, $P=0.07$) in the

burned streams, while NO_3^- was significantly higher in the reference streams (Reference $3.65 \pm 0.94 \mu\text{M}$, $n=4$, versus Burn streams $0.24 \pm 0.67 \mu\text{M}$, $n=8$, $P=0.01$).

3.5. Seasonal patterns of BDOC

Biodegradability of DOC did not change significantly over time in five of the eight streams from which repeat measurements were taken (Fig. 7A). The pattern in DOC biodegradability across the season differed among the three alluvial streams. BDOC % from samples obtained from the Kuparuk River (Site 1) and South River (Site 5) increased (Fig. 7B). In contrast, BDOC % from samples obtained from Oksrukyuik Creek (Site 2) decreased as the season progressed (Fig. 7C).

4. Discussion

Contrary to our hypothesis, we found that streams disturbed by thermokarst and fire did not contain significantly altered labile DOC fractions compared to adjacent reference waters. The quantity, composition and biodegradability of riverine DOC sampled in this study differed primarily by region, likely driven by unique landscape and watershed characteristics (e.g., lithology, soil and vegetation type, elevation, and glacial age). Watershed characteristics influence ecological patterns by controlling the chemistry of soils (Jenny, 1980); plants (Stohlgren et al., 1998); water (Hynes, 1975); and microbial community composition (Larouche et al., 2012). Thus, it is not surprising to observe differences in DOC quantity and character across the three different regions sampled. A circumboreal study across diverse catchments found that DOC loadings also varied by region (i.e., extent of permafrost and runoff) (Tank et al., 2012). The range of BDOC % from streams and rivers measured in this study (4-46%) is similar to other studies of

Arctic riverine BDOC (<10-40%) (Holmes et al., 2008; Mann et al., 2012; Wickland et al., 2007).

4.1. Short-lived effects from fire and thermokarst

Our study tested for differences in DOC quantity and biodegradability across three geographic regions for headwater stream reaches disturbed by fire and thermokarst. DOC in thermokarst outflow is highly biodegradable (Cory et al., 2013; Vonk et al., 2013; Woods et al., 2011), though biodegradability returns to pre-disturbance levels once features stabilized (Abbott et al., 2014). Two potential explanations for the lack of thermokarst impact in this study are the relatively small portion of the watersheds occupied by thermokarst and the fact that the receiving streams were relatively large (2nd and 3rd order, in the case of Twin 1 and 3 in the Feniak region), diluting highly labile DOC exported from thermokarst at the watershed scale. The two comparisons of the Valley of Thermokarst Reference watershed versus the Impacted in the burned landscape also did not show an expected impact attributed to the presence of active layer detachment slides. In this case, the lack of physical and hydrologic connectivity between the slides on the south-facing hillslope and the stream valley bottom, and perhaps the rapid stabilization of the features may explain the lack of a watershed-scale influence. Approximately two to three years had passed since active layer detachment slide initiation when we sampled for BDOC. Moreover, 2011 was a particularly dry summer season with few storm events resulting in limited hydrologic connectivity between disturbed surfaces and the stream. A study in the High Canadian Arctic also concluded that seasonal solute export from watersheds disturbed by thermokarst (disturbed

catchment areas range from 6-46%) were more sensitive to increased soil temperatures and rainfall events than to the presence of active layer detachments (Lafrenière and Lamoureux, 2013).

Cory et al. (2014) concluded that DOC in thermokarst outflow, with little prior exposure to light is >40% more susceptible to microbial conversion to CO₂ when exposed to UV light than when kept dark (Cory et al., 2013). Cory et al. (2014) also found that the majority of DOC (70-95%) transferred from soils through surface waters (e.g., headwater streams, rivers and lakes) in the Arctic simply undergoes photolysis to CO₂ (i.e., some combination of photo-mineralization and partial photo-oxidation), rather than bacterial respiration (i.e., biological mineralization). Therefore, there is strong evidence that highly biodegradable DOC from active thermokarst features may be processed in transit from the hillslope (Abbott et al., 2014), particularly if the flow paths are exposed to light (Cory et al., 2013), which may explain why we did not see significant differences between upstream and downstream thermokarst-impacted reaches in this study. In general, there is conflicting evidence about the effects of thermokarst on surface water biogeochemistry (Dugan et al., 2012; Lamoureux and Lafrenière, 2009; Lewis et al., 2011). In the study of the impact of a gully feature on an Arctic headwater stream, despite the fact that thermokarst outflow had a unique water quality signature from permafrost degradation, there was no discernible impact on the receiving stream, likely because thermokarst discharge was small compared to stream discharge and recovery of the thermokarst disturbance was rapid (Larouche et al., in review). Thus, it is possible that the majority of

the labile DOC liberated via thermokarst will not have a strong overall impact on the biogeochemistry of receiving aquatic ecosystems.

The typical post-burn biogeochemical signal that many have found in lower latitude ecosystems may not manifest in burned Arctic watersheds due to the added complexity of permafrost dynamics that also change due to fire. Monitoring and modeling efforts in the terrestrial system of the Anaktuvuk River Fire scar suggest that tundra surface properties (e.g., greenness, albedo, thaw depth) appear to recover rapidly post-fire (Rocha et al., 2012). DOC quantity and biodegradability may have been altered immediately after the tundra burned but, our sampling four years post-fire may have missed the initial response to fire.

4.2 Picking an appropriate reference for paired watershed studies

We originally planned for the Toolik river sites (Kuparuk and Oksrukyuik) to be the reference sites for the burned streams. Had we not opportunistically sampled the two sites north of the burn boundary or the sites in the Feniak region, we may have attributed differences in water chemistry to fire disturbance rather than landscape characteristics. Even though we detected no effect of fire and thermokarst on BDOC, we had a limited sample size and therefore low power in making this statistical conclusion. We conclude that water chemistry differs significantly by region (Fig. 6), regardless of disturbance. However, when we compare the Anaktuvuk reference sites to the east of the burn boundary with the sites within the burned area from a single sampling date on August 6, 2011 (the only date we were able to sample reference sites outside of the burned boundary) we found significant differences in water chemistry (i.e., higher DOC, NH_4^+ ,

PO_4^{3-} , TDP and lower NO_3^- in the burned streams, data not shown). There could also be differences in BDOC metrics between the Anaktuvuk reference and burned streams, but our sample size is too small to detect this difference.

4.3. Why do DOC pools and biodegradability differ by region?

Landscape age and associated ecosystem differences may explain the differences in BDOC we observed. The Anaktuvuk landscape is substantially older (>700 ka) than the younger surfaces of Toolik (10-400 ka) and Feniak (50-80 ka). An older landscape would host deeper and more decomposed soil organic layers (Hobbie and Gough, 2004), particularly under warmer conditions at a lower elevation, potentially imparting lower BDOC % in streamwater. Elevation likely plays a role with warmer air and soil temperatures in the Anaktuvuk (285 ± 17 m) region compared to Feniak (757 ± 18 m) and Toolik (604 ± 33 m) areas. These landscape characteristics may explain the higher concentrations of DOC, TDN and TDP and the lower % BDOC observed in the streams, regardless of the impact of fire or thermokarst. Recent terrestrial modeling work in the Anaktuvuk burn scar predicted an accumulation of nutrients during the early stages of succession in the soils due to low vegetation cover post-fire that resulted in low plant demand for nutrients, while inorganic nutrients were still being mineralized at similar or enhanced rates (Yueyang Jiang et al., in review). High nutrient accumulation in the soil post-fire could potentially be available as runoff, which would be consistent with our observations of high nitrogen and phosphorus in the Anaktuvuk streams.

The concentration and characteristics of streamwater DOC differ according to its source (McDowell and Likens, 1988). We found that Anaktuvuk stream samples

contained high DOC concentrations of low biodegradability and that the area sampled (i.e., in the southern area of the burn scar) likely receives allochthonous inputs from moist acidic tundra (MAT) communities (Jorgenson, 2009). Conversely, Feniak streams, which receive allochthonous inputs from moist non-acidic tundra (MNAT) (Jorgenson, 2009), contained low DOC concentrations of high biodegradability. In general, the rivers in the Toolik area contained low DOC concentrations of a relatively recalcitrant form. Thermokarst features draining MNAT have higher BDOC compared to MAT, perhaps due to accelerated decomposition of dissolved organic matter from higher N availability in acidic tundra before reaching the stream (Hobbie and Gough, 2004). Thus, the MNAT vegetation type in the Feniak area may explain its high BDOC %.

Arctic rivers and streams are generally high in dissolved organic matter and low in inorganic nutrients (Dittmar and Kattner, 2003). Although there is little evidence for nutrient limitation of DOC degradation, background dissolved inorganic N concentrations were positively correlated with BDOC % in thermokarst outflow (Abbott et al., 2014). Feniak streams also tend to have higher concentrations of NH_4^+ , potentially alleviating any limits on DOC uptake caused by nitrogen availability. Anaktuvuk streams contain an order of magnitude higher concentrations of DOC, TDN and TDP, compared to Feniak and Toolik streams, which is explained by the older landscape age and also perhaps due to the stream type sampled (i.e., all but one of the stream sites sampled in the Anaktuvuk area were of the beaded type which tend to contain more peat and therefore potentially greater amounts of stored carbon, nitrogen and phosphorus). The morphology of streams and particular watershed characteristics such as soil type likely plays an important role in

inorganic nutrient concentrations that may in-turn affect DOC biodegradability. The degree of surface-subsurface connectivity with the hyporheic zone, as well as rates of nutrient regeneration, differs between beaded and alluvial Arctic stream systems (Greenwald et al., 2008).

4.4. Seasonality of BDOC

Contrary to several studies showing highest BDOC during snowmelt, followed by a decrease through the growing season (Holmes et al., 2008; Mann et al., 2012; Raymond et al., 2007; Spencer et al., 2008), we found variable seasonal patterns of BDOC. The majority of these studies are in larger, arctic river systems whereas our study sampled 1st and 2nd order headwater streams. Stream morphology may also play a role since beaded streams are made up of ice-rich polygons that may contain older forms of DOC and are typically colder compared to alluvial systems (Brosten et al., 2006). Thermo-erosion gullies, a common upland thermokarst type, often form from the thaw of ice-rich polygons and the outflow from gullies contained the least biodegradable DOC compared to other feature types, although still elevated compared to reference waters (Abbott et al., 2014). Thus, although polygonal areas are susceptible to thaw via gully formation or beaded stream formation, it is possible that the ice wedges contain low BDOC %. We observed an increase in BDOC % in the Kuparuk River (Site 1) and South River (Site 5), both of which are alluvial systems without any lake influence upstream of the river network (Fig. 7B), whereas we observed a decreasing trend in BDOC % in Oksrukyuik Creek, an alluvial system with a series of lakes upstream of our sampling point (Fig. 7C). In the alluvial streams without lakes, it is likely that after the pulse of labile terrestrial

DOC during the freshet (which our study did not sample), tundra plant and in-stream algal productivity increases as the growing season progresses and in-turn increases stream DOC biodegradability as sources shift from allochthonous to autochthonous. We suggest that the lake effect in the Oksrukyik Creek watershed serves as a reservoir for a pulse of highly labile, aquatic-derived BDOC in the beginning of the growing season, following the flush from the terrestrial ecosystem during the spring freshet. The BDOC in general from the alluvial stream with the lake influence is more labile (BDOC % range 15.7 - 24.6) compared to the alluvial systems without lakes (BDOC % range 0.75 - 13.9) as it leaks from the rich lake environment down the watershed, likely seeding the stream with rich material from the lake across the season.

5. Conclusions

Although active thermokarst outflow contains highly biodegradable DOC (Abbott et al., 2014; Balcarczyk et al., 2009; Cory et al., 2013; Vonk et al., 2013; Woods et al., 2011) and dissolved organic matter biodegradability from boreal soil leachate is lower from burned than unburned soils (Olefeldt et al., 2013) we found no significant effect of fire or thermokarst in the streams we sampled. Our study indicates that landscape characteristics are the dominant control on stream water chemistry and DOC quantity, biodegradability, and aromaticity. Although elevated concentrations and export of sediment and nutrients from thermokarst have been documented (Bowden et al., 2008; Kokelj et al., 2009; Lamoureux and Lafrenière, 2009; Scott and Melissa, 2014), the impact on hydrologic export depends largely on the magnitude and type of thermokarst disturbance, the time from initial disturbance to stabilization, and the hydrologic

connectivity between the feature and downslope aquatic ecosystems (Lewis et al., 2011; Shirokova et al., 2013; Thienpont et al., 2013). Moreover, studies have found that factors such as location of thermokarst in catchment (e.g., north vs. south facing slope) and inter-annual discharge and rainfall runoff variability have greater impact on total dissolved solute fluxes in the Canadian High Arctic (Lewis et al., 2011; Lafrenière and Lamoureux, 2013). Although thermokarst gullies and active layer detachment slides are the dominant thermokarst types in the area we sampled (e.g. ~80% of all the thermokarst in the vicinity of the Toolik Field Station) (Krieger, 2012), their relatively short-lived active export period prior to stabilization may not significantly alter landscape-scale biogeochemical cycling. Conflicting reports of the effects of permafrost disturbance on BDOC suggest that substantial uncertainty remains about the vulnerability of aquatic ecosystems as the permafrost region warms. Given the complexities and interactions of the controlling biogeochemical variables on Arctic dissolved organic matter, monitoring thermokarst and fire impacts at both the site and catchment scales, as well as the consideration of landscape characteristics could address this disconnect.

Author Contribution

Larouche and Abbott designed the experiment, collected and analyzed samples and collaborated closely on the manuscript written by Larouche. Bowden and Jones advised on the design of the experiment, assisted with the data analysis, and edited the final manuscript.

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Table 1*Physical characteristics of sampling sites*

Region	Site ID	Site Name	Stream Type	Stream Order ¹ (Strahler)	Watershed Area ¹ (km ²)	Watershed Elevation ¹ (m)	Watershed Slope ¹ (degrees)	Channel Length ¹ (km)	Bedrock ² (%)
Toolik	1	Kuparuk River	Alluvial	4	132.8	987	8.9	239	3.0
Toolik	2	Oksrukyuik Creek	Alluvial	3	57.2	868	5.2	104	0.0
Anaktuvuk	3	Burn Reference Site 1	Alluvial	3	52.6	213	4.9	128	0.0
Anaktuvuk	4	Burn Reference Site 2	Alluvial	4	167.3	353	5	341	0.0
Anaktuvuk	5	South River	Alluvial	4	96.5	415	4.7	170	0.0
Anaktuvuk	6	North River	Beaded	4	72.5	351	5	96	0.0
Anaktuvuk	7	Valley of Thermokarst Reference	Beaded	3	15.7	373	5.7	23	0.0
Anaktuvuk	8	Valley of Thermokarst Impacted	Beaded	3	26.7	391	5.1	41	0.0
Feniak	9	Bloodslide Reference	Alluvial	2	1.5	750	-	-	-
Feniak	10	Bloodslide Impacted	Alluvial	2	5.2	750	12.1	4	100
Feniak	11	Twin 1	Alluvial	2	23.2	700	9.8	16	20.9
Feniak	12	Twin 3	Alluvial	3	43	826	14.8	31	11.3

Variable Ground Ice ² (%)	Glacial Age ³ (ka)	Ecotype ⁴	Vegetation Code ⁵	Vegetation ⁵	Disturbance Type	Coordinates (UTM)
97.0	200-700	Lowland Birch-Ericaceous Low Shrub	II.C.2.a.	Open Low Mixed Shrub-Sedge Tussock Tundra	Reference	68.6430 -149.4028
91.0	200-700	Lowland Sedge-Willow Fen	II.C.2.h.	Open Low Willow-Sedge Shrub Tundra	Reference	68.6709 -149.1380
0.0	>700	Lowland Willow Low Shrub	II.C.1.b.	Closed Low Willow Shrub	Reference	69.2889 -150.4327
0.0	>700	Riverine Moist Willow Tall Shrub	II.B.1.a.	Closed Tall Willow Shrub	Reference	69.1764 -150.1558
45.7	>700	Lowland Willow Low Shrub	II.C.1.b.	Closed Low Willow Shrub	Burned	68.9973 -150.3080
3.6	>700	Lowland Willow Low Shrub	II.C.1.b.	Closed Low Willow Shrub	Burned	69.0536 -150.4003
0.0	>700	Upland Willow Low Shrub	II.C.2.h.	Open Low Willow-Sedge Shrub Tundra	Burned	68.9350 -150.6861
0.0	>700	Upland Dwarf Birch-Tussock Shrub	II.C.2.a.	Open Low Mixed Shrub-Sedge Tussock Tundra	Burned + ALDs	68.9611 -150.7008
-	200-700	Alpine Wet Sedge Meadow	II.A.3.c.	Wet Sedge Herb Meadow Tundra	Reference	68.2794 -157.0256
0.0	200-700	Alpine Wet Sedge Meadow	II.A.3.c.	Wet Sedge Herb Meadow Tundra	ALD	68.2809 -157.0245
0.0	50-80	Upland Sedge-Dryas Meadow	III.A.2.j.	Sedge-Dryas Tundra	Reference and TS	67.9620 -156.7814
0.0	50-80	Upland Sedge-Dryas Meadow	III.A.2.j.	Sedge-Dryas Tundra	Reference and TS	67.9612 -156.8304

¹ Jorgenson, M., Yoshikawa, K., Kaveskiy, M., Shur, Y., Romanovsky, V., Marchenko, S., Grosse, G., Brown, J., and Jones, B.: Permafrost characteristics of Alaska, Proceedings of the 9th International Conference on Permafrost, Fairbanks, Alaska, 2008, 121-122,

² Nolan, Matt, 2003. "Distribution of a Star3i DEM of the Kuparuk River watershed." Joint Office for Scientific Support, Boulder, CO.

³ Hamilton, T. D., and K. A. Labay (2011), Surficial Geologic Map of the Gates of the Arctic National Park and Preserve, Alaska, U.S. Geological Survey (in cooperation with U.S. National Park Service), Scientific Investigations Map 3125, 1 : 300,000 scale, and accompanying report, 19p

⁴ Jorgenson, M. T., J. E. Roth, P. F. Miller, M. J. Macander, M. S. Duffy, A. F. Wells, G. V. Frost, and E. R. Pullman (2010), An ecological land survey and landcover map of the Arctic Network. Natural Resource Technical Report NPS/ARCN/NRTR—2009/270., edited, National Park Service, Fort Collins, Colorado.

⁵ Viereck, L. A., C. T. Dyrness, A. R. Batten, and K. J. Wenzlick (1992), The Alaska Vegetation Classification, edited by U.S.D.A. Forest Service, 278pp, Gen. Tech. Rep. PNW-GTR-286, Portland, OR.

Table A1**Water chemistry analytes and their respective methods and instruments**

Variable	Method	Instrument
Soluble reactive orthophosphate (PO ₄ ³⁻ -P)	Lachat QuickChem 10-115-01-1-Q	Lachat autoanalyzer
Nitrate (NO ₃ ⁻ -N)	Lachat QuickChem 10-107-06-2-O	Lachat autoanalyzer
Ammonium (NH ₄ ⁺ -N)	Lachat QuickChem 10-107-04-1-B	Lachat autoanalyzer
Dissolved Organic Carbon (DOC)	EPA 415.1 (Combustion)	Shimadzu TOC-V CHP
Total Dissolved Nitrogen (TDN)	Combustion with chemiluminescence	Antec 750
Total Dissolved Phosphorus (TDP)	EPA 365.2	Shimadzu UV-Spectrophotometer 1601120V
Base cations	ICP-OES	Perkin Elmer Optima 3000DV
Micronutrients	ICP-OES	Perkin Elmer Optima 3000DV
Metals	ICP-OES	Perkin Elmer Optima 3000DV
Anions	Ion Chromatography	Dionex IonPac AS14A
Alkalinity	Titration	Tim800 ABU900 Autoburette

Table A2

Summary of DOC metrics by site. The mean of each sampling (n) is reported with standard error (SE). ‘ - ’ indicates no SE due to sample size (n = 1)

Site ID	n	Initial DOC (uM)	SE	TDN (uM)	SE	BDOC Loss (uM)	SE	Total BDOC (% Loss)	SE	SUVA ₂ ⁵⁴	SE
1	5	219	10	126	3	40	4	17.5	1.3	1.88	0.03
2	5	300	22	129	4	52	10	19.5	1.7	2.36	0.09
3	1	1313	-	152	-	178	-	13.4	-	5.90	-
4	1	642	-	142	-	72	-	15.5	-	2.57	-
5	5	1354	138	153	6	100	37	7.1	1.8	4.55	0.10
6	5	984	55	158	12	70	24	6.7	2.1	4.66	0.19
7a	5	924	86	141	6	96	23	10.3	1.8	4.89	0.25
7b	4	979	65	147	3	112	27	11.1	1.8	4.82	0.40
8a	5	1185	103	148	4	131	24	11.5	2.9	5.17	0.49
8b	4	1208	73	155	1	115	18	9.4	1.4	5.27	0.48
9	1	331	-	134	-	95	-	28.8	-	2.60	-
10	1	388	-	170	-	157	-	40.1	-	2.07	-
11a	1	319	-	138	-	159	-	45.5	-	1.31	-
11b	1	268	-	139	-	112	-	39.5	-	2.09	-
12a	1	298	-	136	-	121	-	39.9	-	1.50	-
12b	1	267	-	129	-	93	-	34.8	-	1.62	-

Table A3

Summary of water chemistry by site. The mean of each sampling (n) is reported with \pm standard error SE for those sites that had more than one sampling. Numbers in () represent sample size when different from the majority 'n'

Site	n	TSS	Alkalinity	TDN	NH ₄ ⁺	NO ₃ ⁻	TDP	PO ₄ ³⁻
1	37	1.03 \pm 0.19	305 \pm 9	14.1 \pm 0.3	0.72 \pm 0.13 (3)	5.87 \pm 0.22	0.03 \pm 0.01	0.07 \pm 0.03 (3)
2	37	0.47 \pm 0.11	314 \pm 13	16.7 \pm 0.5	0.61 \pm 0.05 (3)	5.28 \pm 0.31	0.01 \pm 0.00	0.04 \pm 0.01 (2)
3	1	2.05	411	50.3	0.16	-	0.24	0.11
4	1	0.00	420	25.1	0.11	4.27	-	0.04
5	42	0.72 \pm 0.17	699 \pm 48	37.7 \pm 0.7	0.33 \pm 0.11	0.49 \pm 0.11	0.23 \pm 0.01	0.10 \pm 0.01
6	41	2.03 \pm 0.61	364 \pm 28	53.1 \pm 0.7	0.47 \pm 0.15	0.01 \pm 0.01	0.45 \pm 0.01	0.17 \pm 0.04
7a	38	2.58 \pm 0.58	151 \pm 12	38.2 \pm 1.3	0.53 \pm 0.19	0.17 \pm 0.04	0.42 \pm 0.03	0.19 \pm 0.06
7b	3	0.67 \pm 0.67	113 \pm 21	31.5 \pm 1.9	0.22 \pm 0.09	0.00 \pm 0.0	0.34 \pm 0.03	0.16 \pm 0.05
8a	38	2.68 \pm 0.45	210 \pm 15	45.1 \pm 1.4	0.23 \pm 0.03	0.02 \pm 0.01	0.58 \pm 0.04	0.21 \pm 0.07
8b	3	4.92 \pm 1.42	203 \pm 87	43.0 \pm 7.0	0.41 \pm 0.21	0.37 \pm 0.22	0.52 \pm 0.12	0.21 \pm 0.06
9	1	0.20	2633	9.9	0.5	0.3	0.0	0.1
10	1	44.6	2114	7.8	0.6	2.5	-	0.1
11a	1	0.21	661	12.4	1.24	4.92	0.09	0.13
11b	1	119	802	11.7	0.55	4.72	0.11	0.11
12a	1	17.24	1402	14.1	0.56	5.00	0.04	0.11
12b	1	7.20	1381	12.5	0.97	4.98	0.04	0.09

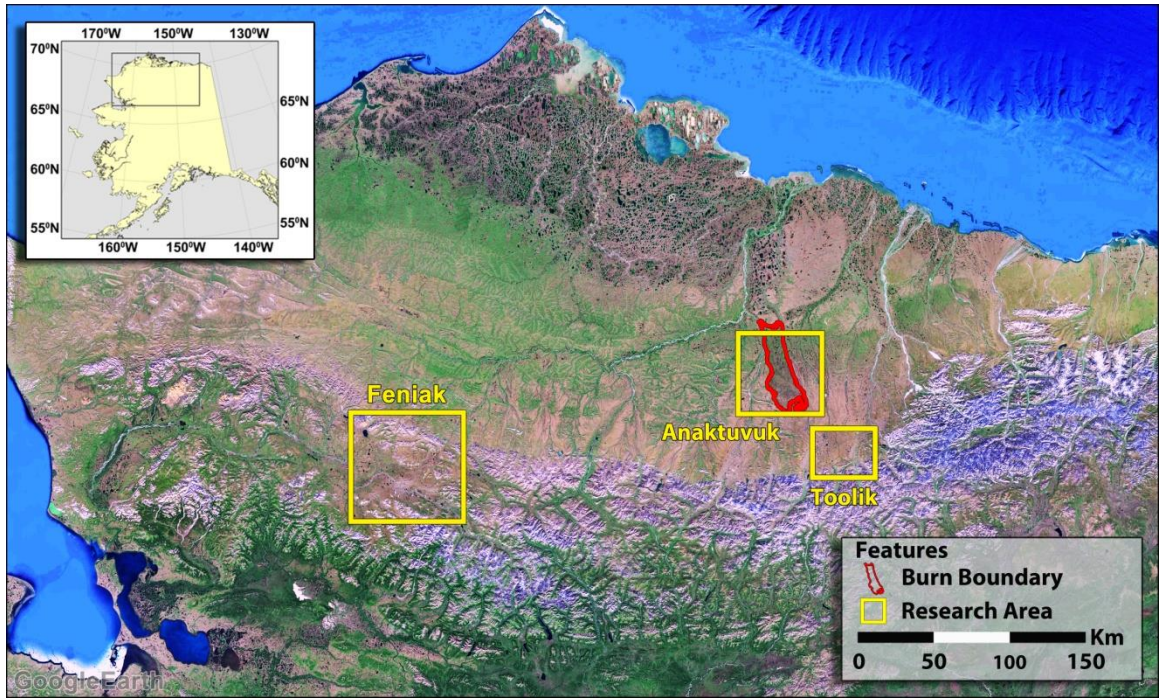


Figure 1. Map of study areas. Map credit: J. Noguera, Toolik Field Station GIS and Remote Sensing Facility.

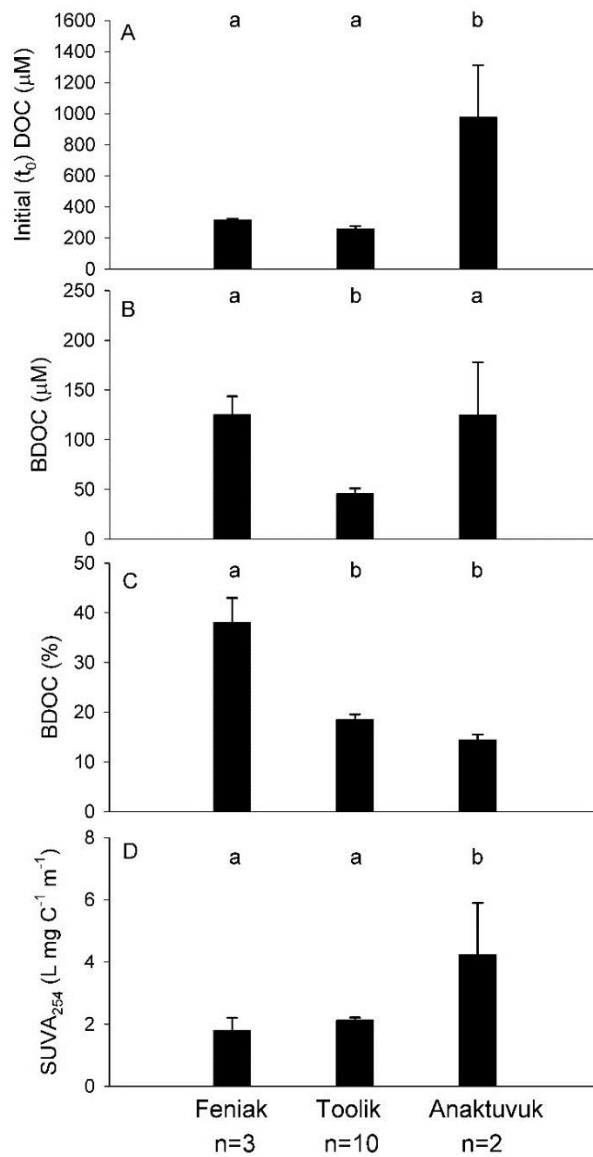


Figure 2. Comparison of reference sites of the three regions for stream DOC quantity (A); Biodegradability in terms of absolute loss (B) and percent loss (C) after 40 days; and SUVA₂₅₄ (D). Means and standard error are reported. Sample size (n) represents a sampling of a stream on a given day. The ‘Feniak’ group represents 3 stream reaches sampled one time in the Feniak region. The ‘Toolik’ group represents 2 stream reaches sampled 5 times over the season. The ‘Anaktuvuk’ group represents 2 reaches sampled once outside of the burn boundary. Different letters represent significant differences between regions, $\alpha = 0.05$.

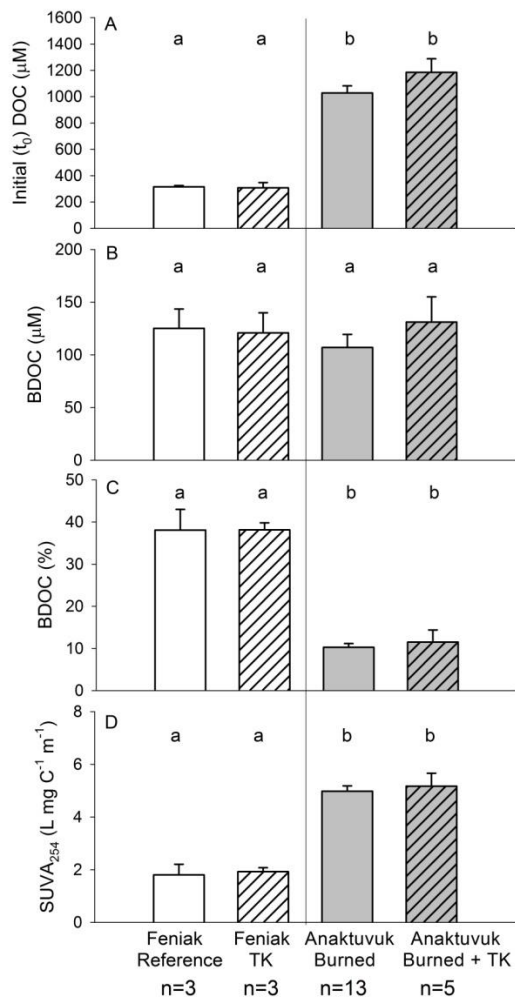


Figure 3. Assessing the impact of thermokarst on stream DOC quantity (A); Biodegradability in terms of absolute loss (B) and percent loss (C) after 40 days; and SUVA₂₅₄ (D). Means and standard error are reported. Sample size (n) represents an individual sampling event of stream reach. ‘Feniak Reference’ and ‘Feniak TK’ groups each represent 3 stream reaches sampled upstream and downstream of active thermokarst features one time in the Feniak region. The ‘Anaktuvuk Burned’ group represents 3 stream reaches, one of which was sampled five times and two of which were sampled four times within the fire boundary. The ‘Anaktuvuk Burned + TK’ group represents one stream reach within the fire boundary that contains multiple active layer detachment slide thermokarst within its watershed, sampled five times over the season. ANOVA was used to detect differences for the two comparisons (Reference vs. TK and Burned Reference vs. Burned + TK). Similar letters indicate no differences.

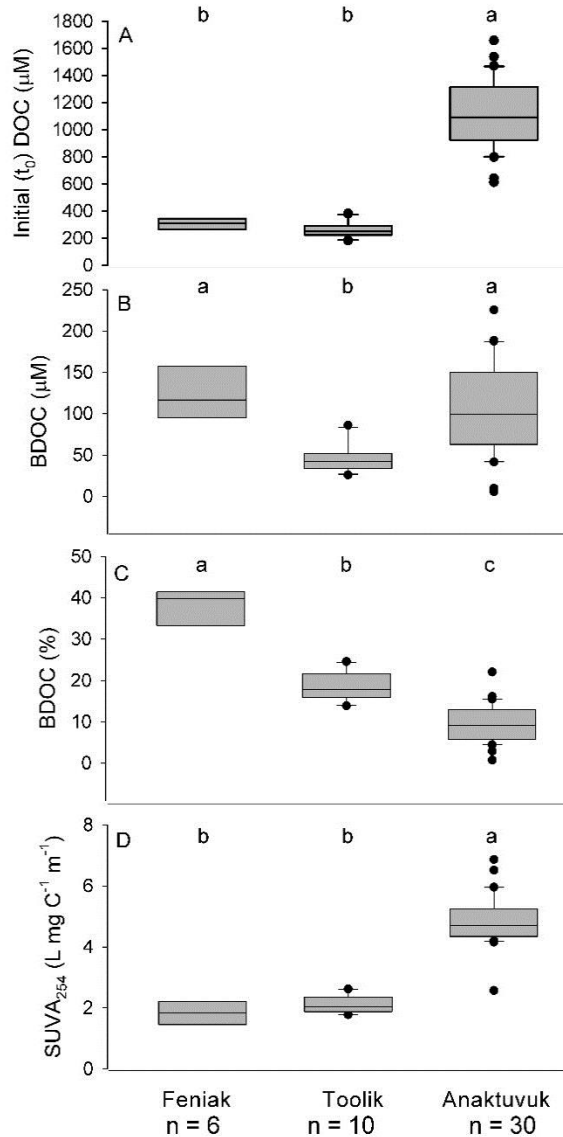


Figure 4. Assessing the impact of region (regardless of treatment) on stream DOC quantity (A); Biodegradability in terms of absolute loss (B) and percent loss (C) after 40 days; and SUVA₂₅₄ D). Box plots represent median, quartiles, minimum and maximum within 1.5 times the interquartile range (IQR), and outliers beyond 1.5 IQR. Sample size (n) represents a sampling of a stream on a given day. The ‘Feniak’ group represents 6 stream reaches sampled one time in the Feniak region. The ‘Toolik’ group represents 2 stream reaches sampled 5 times over the season. The ‘Anaktuvuk’ group represents 6 burned stream reaches sampled 4-5 times plus the 2 unburned sites sampled once. Different letters represent significant differences between regions, $\alpha = 0.05$.

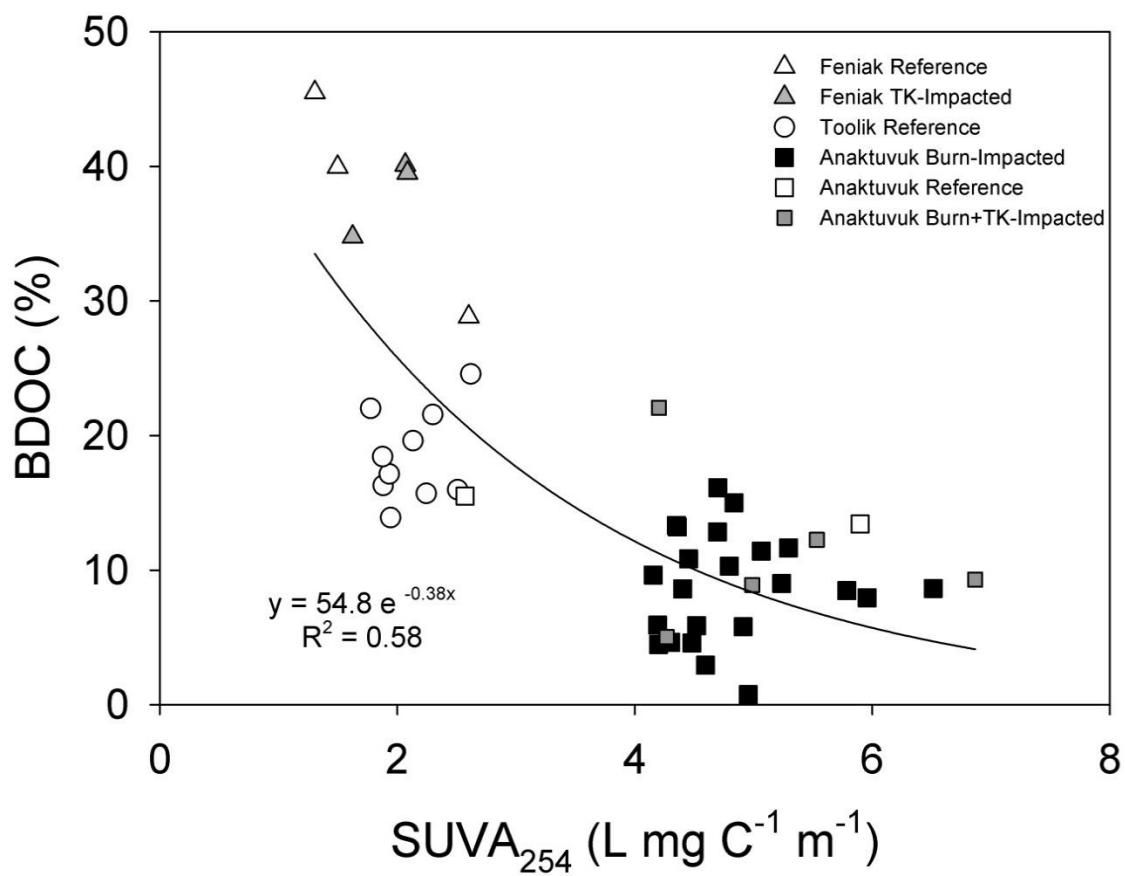


Figure 5. $SUVA_{254}$, ($L\ mg\ C^{-1}\ m^{-1}$) versus BDOC 40-day loss (%) for streams grouped by area and disturbance type.

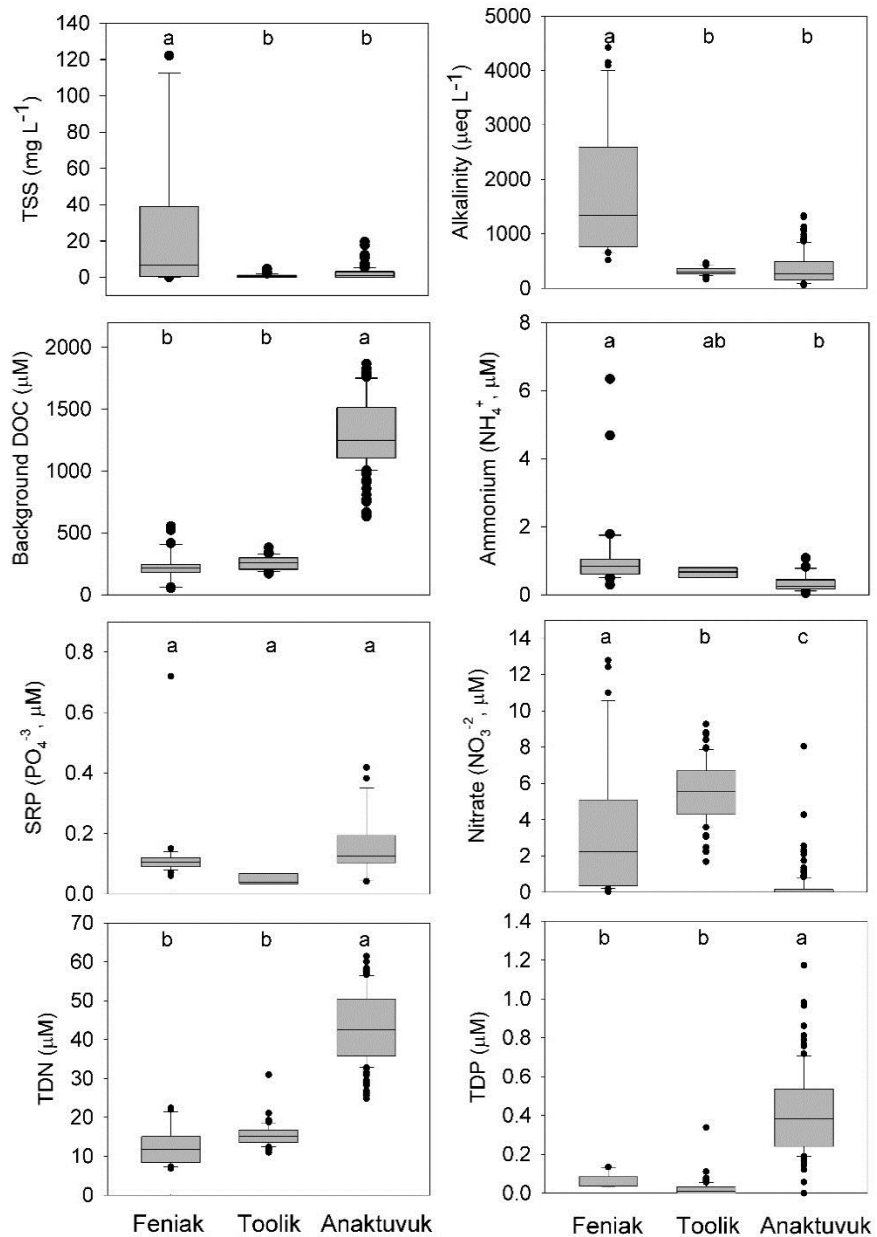


Figure 6. Biogeochemical characteristics of streams within each region (includes all available data, not just from BDOC sampling sites/dates). Box plots represent median, quartiles, minimum and maximum within 1.5 times the interquartile range, and outliers beyond 1.5 IQR. Different letters represent significant differences between regions, $\alpha = 0.05$. Sample sizes vary (see text).

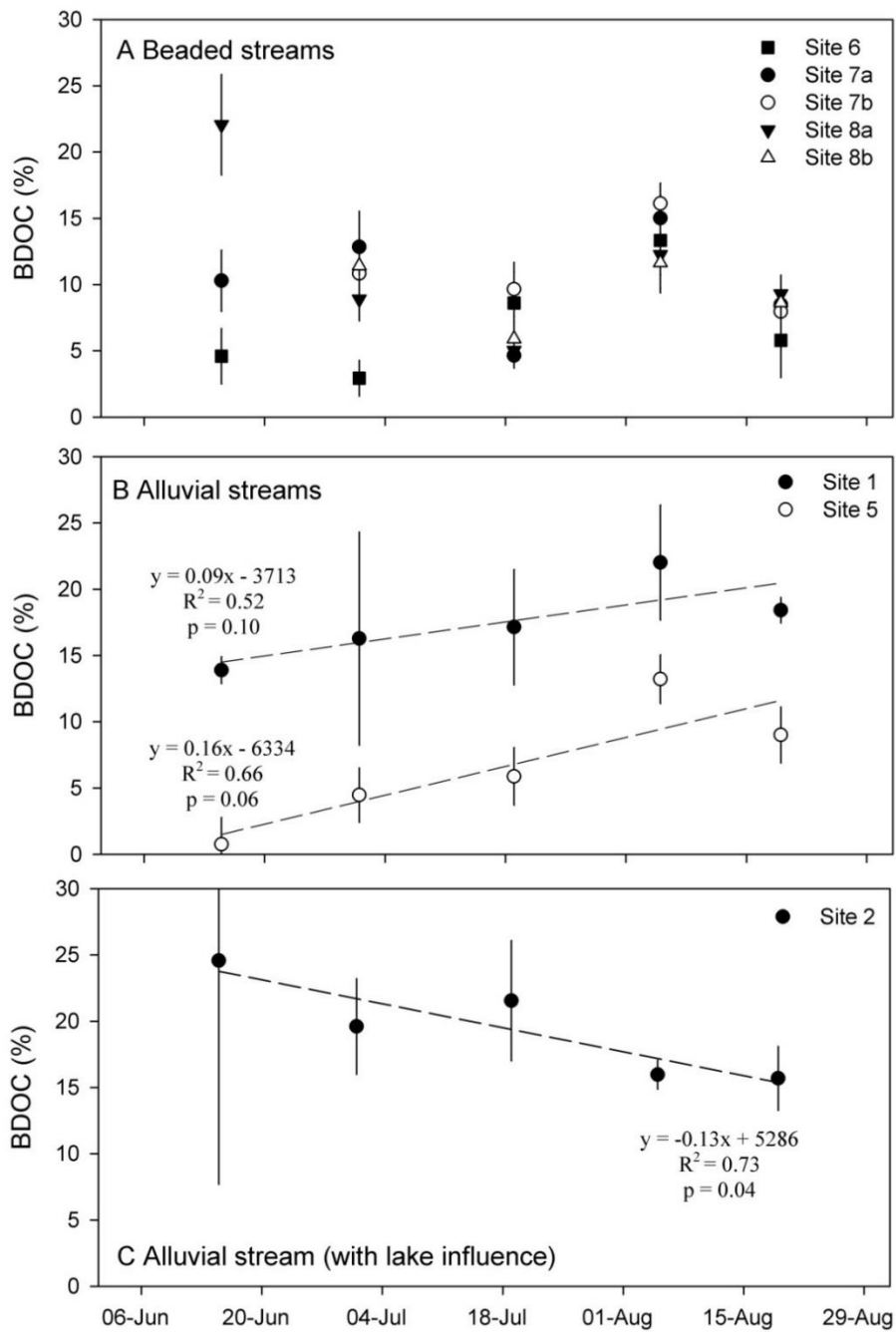


Figure 7. Seasonal trends in BDOC (%): A) Beaded stream sites – no significant trends; B) alluvial sites without any lake influence – significantly increasing trends; C) alluvial site with lake influence upstream - significantly decreasing trend. Each symbol and associated error bars represent the mean BDOC (%) and the standard error of the four field replicates.

CHAPTER 5: CONCLUSIONS

5.1 Perspective

Cryospheric processes and modes of permafrost degradation including thermokarst (e.g., solifluction, initiation and expansion of thaw lakes, polygonal thaw, water tracks, collapse scars, non-patterned thaw, etc.) are a natural part of ecosystem development and geomorphic progression in permafrost-dominated landscapes (Davis 2001). For millennia, thermokarst has played an important role in shaping permafrost landscapes and these processes occur even in relatively stable climates, but are more common in regions of warm, discontinuous permafrost compared to zones of cold, continuous permafrost simply because the energy required to negotiate the thermal change required for thermokarst initiation is lower (French 2007). Thus, there is the presumption that thermokarst development in Arctic and High Arctic regions is less important based on the fact that a lot of energy is required to shift the thermal regime of continuous, cold permafrost because the active layer is relatively shallow and the season of thaw from solar radiation is quite short (French 2007). Permafrost has warmed considerably (2-4°C) throughout the Northern Hemisphere since the 1970s, with colder permafrost sites warming more rapidly (Romanovsky et al. 2010). Recent climate warming and rising permafrost temperatures (along with rising rates of precipitation and potentially wildfire) have coincided with an increase in the frequency and magnitude of thermokarst development (Jorgenson et al. 2006, Lantz and Kokelj 2008), particularly during extreme summer warming events (Balsler et al. 2014). Currently thermokarst features impact 1.5-2% of the landscape in the continuous permafrost zone of the

foothills of the Brooks Range, Alaska, but statistical estimates of ground ice distribution across all permafrost zones indicates that 20-40% of the landscape is vulnerable to thermokarst activity (Zhang et al. 2000).

There is recent evidence that the permafrost thawed and released a massive amount of carbon to the atmosphere 56 million years ago during the Paleocene-Eocene Thermal Maximum, leading to a 5°C increase in global mean air temperature over several thousand years (DeConto et al. 2012). There appears to have been relatively less loss of carbon due to climate change during the early Holocene ~9,000-5,000 years ago in Arctic air temperatures of 2-4°C. On a geologic timescale, it is unknown whether increased thermokarst activity will significantly alter the global carbon cycle via the permafrost carbon feedback. Given the current anthropogenic influence on the climate system and the potential increase of more than 5° beyond the next century, it is of strong interest to quantify and predict how potential changes in future permafrost states will impact local and global biogeochemical cycling, particularly since the permafrost carbon feedback is not currently considered in greenhouse gas emissions negotiations. There is increasing interest by the scientific community in the spatial and temporal dynamics of thermokarst from a wide diversity of disciplines including: landscape ecology, hydrology, engineering, and biogeochemistry (Jones et al. 2013).

It has been suggested that thermokarst disturbances will likely manifest as patchy, ‘pulse’ disturbances across the landscape, yet the localized hydrobiogeochemical impacts have the potential to be more severe than the ‘press’ modes of permafrost degradation (i.e., active layer deepening and widespread thaw) (Frey and McClelland 2009). Recent

work quantifying aquatic solute fluxes and concentrations from thermokarst has shown that the degree of hydrologic export depends on the magnitude of the disturbance and mass-wasting of hillslope material (i.e., feature size and type); the duration of feature evolution and activity; and the hydrologic connectivity (i.e., proximity to downslope aquatic ecosystems; presence of water tracks; rainfall events). The findings presented in this dissertation lends support to some of these key considerations and are discussed in greater detail in the Emerging Themes section.

Thermokarst currently impacts only ~2% of typical arctic landscapes, but they are important indicators of change. We observed subtle impacts at the local (feature) scale, even with recovering gully thermokarst features. Multi-element, process-based simulation modeling suggests that thermokarst mobilizes large quantities of carbon, nitrogen and phosphorus. Losses of deep soil carbon and nutrients may not recover for decades to centuries (Pearce et al. 2014). This raises important questions regarding the large-scale ecological responses of arctic aquatic ecosystems to localized permafrost thaw. In particular, is the development of thermokarst merely an indicator of climate change or is it a direct agent of climate change? Increased severity and frequency of pulse disturbances in the future, whether the local impacts are subtle and ephemeral (as the case in this dissertation research) or severe and long-lasting, will collectively represent a vast amount of nutrients and organic matter mobilized from the tundra on the Pan-Arctic scale. The mass flux of mobilized sediment, carbon and nutrients from this vulnerable stock of organic matter will end up somewhere, whether in gaseous form in the

atmosphere, or physically retained within or taken up by hillslope vegetation or soil microbes, or in dissolved form along the river network en route to the Arctic Ocean.

5.2 Emerging Patterns from this Dissertation

5.2.1. Aquatic export is ephemeral, depending on feature stabilization and storm activity

An important part of the gully thermokarst portion of this research was calculating the mass balance of sediment and nutrients at the intersection of the thermokarst hillslope tributary (TRIB) with the receiving stream reaches (REF and IMP) (an example from I-Minus2 is shown in Fig. 1). We calculated cumulative seasonal load by multiplying the average seasonal concentration of sediment or nutrient by daily discharge (or stream flow) and summing all the daily loads for the individual seasons. Theoretically, the Reference (REF) reach load plus the load of the TRIB should equal the load of the Impacted (IMP) reach. We expected that the tributary would contribute high loads of sediment and nutrients, and therefore elevate the load of the Impacted reaches compared to the Reference reaches.

Figs. 2-4 report the cumulative seasonal load in kilograms (kg) for the REF+TRIB and the IMP locations for comparison. The error bars are propagated uncertainties from sources of error (i.e., streamflow measurement; sample collection; sample preservation/storage; and laboratory analysis) as reported in Harmel et al. (2006). The sediment load from the hillslope tributary elevates the load of the Impacted reach compared to the Reference at both stream sites (Fig. 2). The impact of the sediment loading declines over the three study seasons, likely due to fewer storms in each season

(i.e., 2009 and 2010 were wet, stormy summers and 2011 was a very dry summer without any notable events). But we cannot discount the possibility that the gully features exported less sediment as they stabilized over time. The contribution of dissolved carbon, nitrogen and phosphorus (dissolved organic carbon, DOC; inorganic nutrients: soluble reactive phosphorus, SRP; ammonium, NH_4^+ ; and nitrate, NO_3^-) from the tributary was negligible for I-Minus2 (Fig. 3) and moderate for the Toolik River (Fig. 4), although not significant (i.e., error bars overlap). I conclude that the hydrologic export from stabilizing gully features is not as significant as previously anticipated when we first began this research study.

5.2.2. Hydrologic connectivity plays an important role in the degree of aquatic export

Hydrologic connectivity plays an important role in the magnitude of hydrologic export. Here I define the hydrologic connectivity as the distance between a feature and the receiving stream or the greater opportunity to connect to receiving streams via water tracks, a common hydrologic drainage feature of arctic tundra hillslopes. Both gully thermokarsts in this study were somewhat distant (~ 450m) from the downslope streams, which provided swaths of vegetation to act as potential filtration beds that could retain sediment and remove inorganic nutrients (in the case at I-Minus2). At Toolik River, the outflow from the gully feature follows a defined water track while at I-Minus2 the water flows in an anastomosing pattern through a swath of vegetation. Both features were also intersected by water tracks which ‘hydrologically connected’ the thermokarst outflow to the stream, particularly during storm events. This hydrologic connectivity plays two

important roles in the export of sediment and nutrients from thermokarst features. First, greater hydrologic connectivity potentially increases the efficiency of sediment delivery to streams. Concurrently, greater hydrologic connectivity may increase the hydrologic loading to a stream, potentially diluting the geochemical signature of the outflow before entering the stream. Whether greater hydrologic connectivity increases or decreases sediment and solute loading to receiving waters is dependent on the particular nature (i.e. configuration or ‘plumbing’) of the hydrologic connection.

For example, we found different responses at the Toolik River site compared to the I-Minus2 site which we attribute to different patterns of hydrologic connectivity at the two sites. At I-Minus2 the low nutrient concentration and low specific conductance of the water track dilutes the high nutrient concentration outflow of the thermokarst when the two converge on the hillslope below the feature (Fig. 5), playing a greater role in thermokarst outflow dilution than a delivery mechanism. Additionally, the swath of vegetation between the feature and stream likely acts as a filtration bed, trapping sediment and immobilizing nutrients before reaching the receiving stream. Conversely, the water track located above the feature at Toolik River may act more as a delivery mechanism of thermokarst material to the stream, than a dilution mechanism (Fig. 5).

The non-metric dimensional scaling analysis portrays a depiction of the biogeochemical signature at the five sampling locations at each gully feature. The distinct signature of thermokarst outflow from each gully shifts toward a stream water signature in transit downslope to the receiving stream, due likely to a combination of the presence of intersecting water tracks (i.e., dilution effect) and the vegetation acting as a trickle

filter for nutrient uptake and sorption. Although many studies have observed elevated concentrations in thermokarst outflow compared to reference waters and therefore conclude that upland thermokarst are likely to have a persistent and widespread effect on aquatic ecosystems, our work suggests that the geochemical signal diminishes upon reaching the valley bottom.

5.2.3. Impacts on stream biological function

As reported in Chapters 2 and 3 sediment and nutrient loading measured in the receiving streams was fairly subtle. Nevertheless, I was able to detect significant differences in nutrient uptake and whole-stream metabolism, in benthic standing stocks and chlorophyll-*a*, and in macroinvertebrate community composition were detected, suggesting that thermokarst outflow from previous years' may have long-lasting, cascading effects on biological functions. A long-term fertilization experiment on the Kuparuk River on the North Slope of Alaska had significant bottom-up impacts from low-level phosphorus additions including increasing bacterial activity, algal production, rates of epilithic respiration and macroinvertebrate abundance (Slavik et al. 2004). Moreover, after nearly a decade of continuous summer fertilization of phosphorus, a major shift in aquatic moss species occurred (Bowden et al. 1994, Slavik et al. 2004). However, sediment loading could potentially offset any nutrient fertilization effects from thermokarst (i.e., interfering with light availability and therefore productivity). Thus, it is hard to predict the consequences of nutrient and sediment loading from thermokarst to aquatic ecosystems when there is very limited information on the ecological response to these types of disturbances.

Finally, it is necessary to acknowledge that the differences in ecological function detected in this study could potentially be due to inter-reach differences and the geomorphic form of the receiving stream, particularly at I-Minus2. Clearly, more work is necessary at the feature scale to elucidate the patterns of the biological responses from disturbed aquatic ecosystems.

5.2.4. Stream geomorphology

Stream geomorphic type may potentially play a role in the degree to which a receiving stream is vulnerable to thermokarst disturbance, as shown by the different response between the alluvial and peat-bottomed impacted streams. Chapter 2 reports on a tundra stream (I-Minus2) that has a high-gradient, fast-flowing, cobble-bottom form in contrast to the Toolik River (Chapter 3) study reach which has a low-gradient, slow-flowing, peat-bottom, beaded stream type. Alluvial, cobble-bottom streams like I-Minus2 have greater depths of thaw compared to peat-bottom streams and therefore more connectivity between the hyporheic zone and the in-stream surface water (Greenwald et al. 2008). This distinguishing characteristic (stream geomorphology) may potentially play a role in the degree to which a receiving stream is responsive to thermokarst disturbance. For example, an alluvial stream may be more responsive to allochthonous inputs from thermokarst from a functional perspective. Elevated nutrient loading to an alluvial stream may more readily infiltrate into the hyporheic zone – a biogeochemical hotspot for nutrient uptake and regeneration – and induce a change in metabolism or uptake. On the other hand, sediment loading into an alluvial stream may clog the interstitial volume of the streambed, affecting hyporheic exchange as well as the benthic primary producers

and whole-stream metabolism (Uehlinger and Naegeli 1998). In accordance with the original hypothesis (i.e., that the negative effects of sediment loading would offset the stimulatory effects of nutrient loading), the results at I-Minus2 support this hypothesis with lower observed rates of nutrient uptake and metabolism in the Impacted reach. The Toolik River may have responded preferentially to the nutrient loading. The Toolik River Impacted reach had higher algal biomass in two of the three years and higher rates of gross ecosystem production in 2011, suggesting that subtle nutrient loading from a recovering thermokarst feature may influence downstream ecosystem structure and function.

5.2.5. The role of landscape characteristics

Chapter 4 concludes that DOC concentrations, biodegradability of DOC, and water chemistry varies primarily by the region from which streams were sampled, and not by the impact of wildfire or thermokarst disturbance as expected. Possible explanations for this finding are that the overall flux of labile DOC is low compared to the hydrologic load of the receiving stream (i.e., a dilution effect) or that our results support the current view that labile DOC liberated from thermokarst features may be processed upon being exposed to light and/or metabolized in transit downslope before reaching receiving waters (Cory et al. 2013, Abbott et al. 2014).

Although the findings in Chapter 4 suggest that thermokarst and fire do not matter to biodegradable DOC flux, it is also possible that other factors may have obscured real differences. For example, this study was conducted four years after the fire and so I may have missed early differences. Some researchers have suggested that it may take several

years for black carbon to ‘condition’ and become mobile (Abiven et al. 2011, Hockaday et al. 2007) and so I may have sampled too early. Finally, we cannot discount that the statistical power of this opportunistic study was too low to detect an impact. However, the weight of evidence suggests that the differences that were caused by wildfire and thermokarst were not large compared to differences in landscape type. I conclude, therefore, that it would be prudent for future studies to take landscape characteristics into account when quantifying and predicting the impact of permafrost thaw on dissolved organic matter flux at regional scales.

Fig. 6 describes a conceptual model incorporating the key findings from the landscape characteristic perspective within the broader context of permafrost thaw. For example, based on the study from Chapter 4 we may expect several different impacts of thermokarst on streams depending on the landscape context. First, older landscapes host deeper layers of organic matter that have undergone more decomposition over time compared to younger surfaces with shallow layers of less decomposed material. In older landscapes, we might expect to see high DOC and nutrient flux of low quality while in younger landscapes we might expect to see low DOC and nutrient flux of high quality. Second, vegetation type (specifically, moist acidic and moist non-acidic tundra) may also play a role with high nutrient availability in acidic tundra potentially alleviating limitations on decomposition, resulting in lower quality DOC flux to streams. Finally, watersheds with lakes may contribute a larger overall flux of biodegradable DOC compared to watersheds without lakes due to pulses of high quality, aquatic-derived DOC, particularly during the spring freshet.

5.3 Strengths and Weaknesses and Scaling Findings

The work presented in Chapters 2 and 3 is important because there are only a handful of studies that have addressed thermokarst impacts on seasonal solute concentration or total fluxes at the watershed scale (Lewis et al. 2012, Lafrenière and Lamoureux 2013) and/or the higher-order impacts of disturbance on biological function (Thompson 2009, Mesquita et al. 2010, Calhoun 2012, Moquin et al. 2014). I have done both with this study. It would have been useful to have conducted this comprehensive, multi-year study immediately after disturbance to quantify the initial impacts on ecosystem structure and function. When the gullies were in their active phases of formation, our inter- and intra-seasonal sampling approach may have been able to more easily the variables that control nutrient and sediment loading downstream (i.e., storm or thermal events). On the other hand, had we conducted this work at that early point we may have concluded that gully impacts have severe impacts on downstream reaches when in fact they appear to be fairly resilient, at least on the decadal scale since initial disturbance. Lastly, I opted not to ‘scale up’ the findings from this feature-scale study because the sample size of two thermokarst gullies that were both in similar stages of recovery is limited. To explore how the measures of metabolism and nutrient uptake rates and total solute fluxes might scale up to the area of headwater streams impacted by thermokarst in the North Slope region would require an examination of many more features in different stages of recovery.

Scaling the collective research from studies of thermokarst features on downslope rivers and streams is important and currently lacking in this field of research. Questions

of interest with regard to scale and modeling the aquatic impacts across the landscape include: 1) How should we scale the impacts of large features versus small features and their impacts on large and small lakes, rivers and streams? 2) Is there a threshold of feature type and size combined with stream or river or lake size when a geochemical or biological impact may or may not be detected? For example, retrogressive thaw slumps significantly impact the geochemistry flux of streams since these features can degrade permafrost to depths of 10 meters or more and the impacts can be detected at the 10^2 km² watershed-scale (Malone et al. 2013). Conversely, shallower disturbances such as active layer detachment slides may not dramatically impact geochemical load to impacted waters and they typically recover fairly quickly (< decade). Large retrogressive thaw slumps (~ 40 ha) have been shown to severely impact both large rivers (5th order) (Calhoun 2012) and smaller streams (Malone et al. 2013). Chapters 2 and 3 in this work that relatively small gully features do not significantly impact 2-order headwater streams. As more studies are conducted in this field, a meta-analysis of the degree of aquatic impact across various combinations of feature type and size and size of impacted aquatic systems will be important for putting the results from these feature-scale studies into the larger, landscape context.

The work presented in Chapter 4 is the first of its nature to sample receiving stream waters impacted by a combination of both fire and thermokarst for DOC biodegradability. Recent work has quantified the highly biodegradable nature of DOC coming directly out of thawing permafrost or thermokarst features (Cory et al. 2013, Abbott et al. 2014), but no study has tested upstream and downstream of a thermokarst

for differences in DOC biodegradability. Unfortunately, our experimental design is not ideal since we were limited to the whims of natural disturbance and site accessibility. Ideally, if we had a single landscape unit with measurements pre- and post-fire and/or thermokarst or multiple watersheds with similar characteristics, it would have been more informative to the scientific community if we had quantified inter-disturbance BDOC variability controlled for by region or watershed characteristics.

5.4 Future Research

It remains to be determined how general permafrost thaw will affect the structure and function of arctic streams in the future. Further feature-scale research that is scalable to a landscape perspective is needed to quantify the hydrologic export from thermokarst features, across feature morphology, activity and landscape type, much like the approach led by Abbott et al. (2015) in order for these important processes to be incorporated into both ecosystem and landscape-scale elemental and terrain models (Pearce et al. 2014, Balsler and Jones, in preparation).

The findings presented in this dissertation provide an evaluation several years after the initial disturbance of the geochemical loading and biological response of headwater stream reaches to gully thermokarst. Additionally, a perspective on the variation in biodegradable dissolved organic carbon and water chemistry in headwater streams impacted by thermokarst and fire, both of which are potential key stressors that will become increasingly important as permafrost landscapes evolve under a changing climate. Future monitoring of thermokarst and fire impacts should include the following important considerations so that regional and global climate models can be better

informed and constrained with regard to patterns of disturbance: feature type, activity and position on the landscape in relation to water tracks; watershed and landscape characteristics (glacial age, elevation, position along the river network, vegetation type); focus on loadings and flux (rather than just concentrations) of nutrients, sediment and biodegradable organic matter to better account for the movement and loss of key elements; and finally, a greater effort assessing the biological responses (e.g., metabolism and nutrient uptake, community composition and diversity) to permafrost thaw. Arctic ecologists are tasked with filling these data gaps with respect to predicting the response of arctic headwater streams to permafrost thaw, within the overall, complex ecosystem response, so that we can develop an understanding of the consequences of climate change in a vulnerable region of the world.



Figure 1. Site photo at the intersection of the hillslope tributary (TRIB - named T3 in Chapters 2 and 3) for the I-Minus2 gully and receiving stream (upstream of the tributary, Reference, REF; downstream of the tributary, Impacted, IMP). Note that the thermokarst gully at this site is located approximately ~500 meters upslope from this viewpoint. The following graphs for cumulative seasonal load use the REF, IMP and TRIB naming convention (synonymous with M2, M3, and T3 naming convention in Chapters 2 and 3). Theoretically, the mass load at REF plus TRIB should equal the IMP load. If there was significant contribution from the hillslope TRIB, the IMP load should be elevated compared to the REF load.

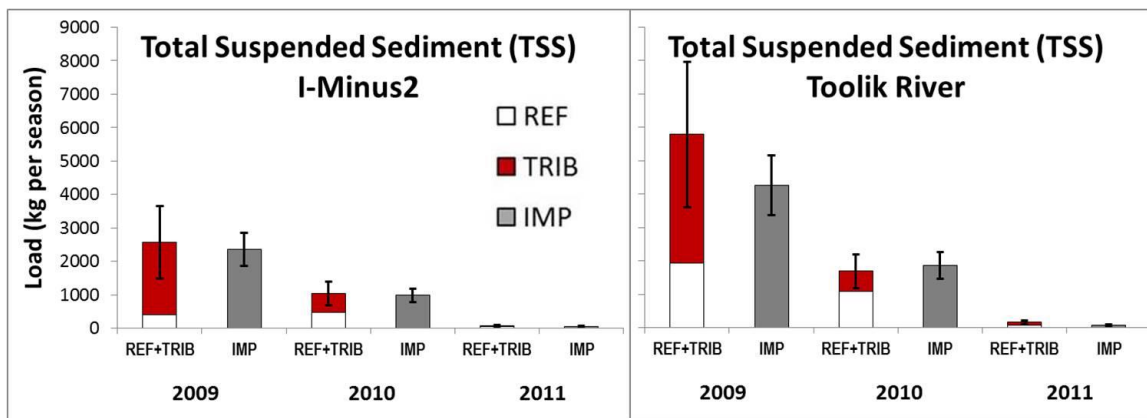


Figure 2. Cumulative seasonal load estimates for Total Suspended Sediment (TSS) for I-Minus2 (left) and Toolik River (right) for all three study seasons. Cumulative seasonal load was calculated by multiplying the seasonal mean concentration of TSS for each sampling site (REF, IMP, TRIB) and multiplying by the daily mean discharge and summing all the days in the collection season (mid-June through mid-August). Refer to Figure 1 for the site location labels. Error bars represent error propagation from sources of error as explained Harmel et al. (2006).

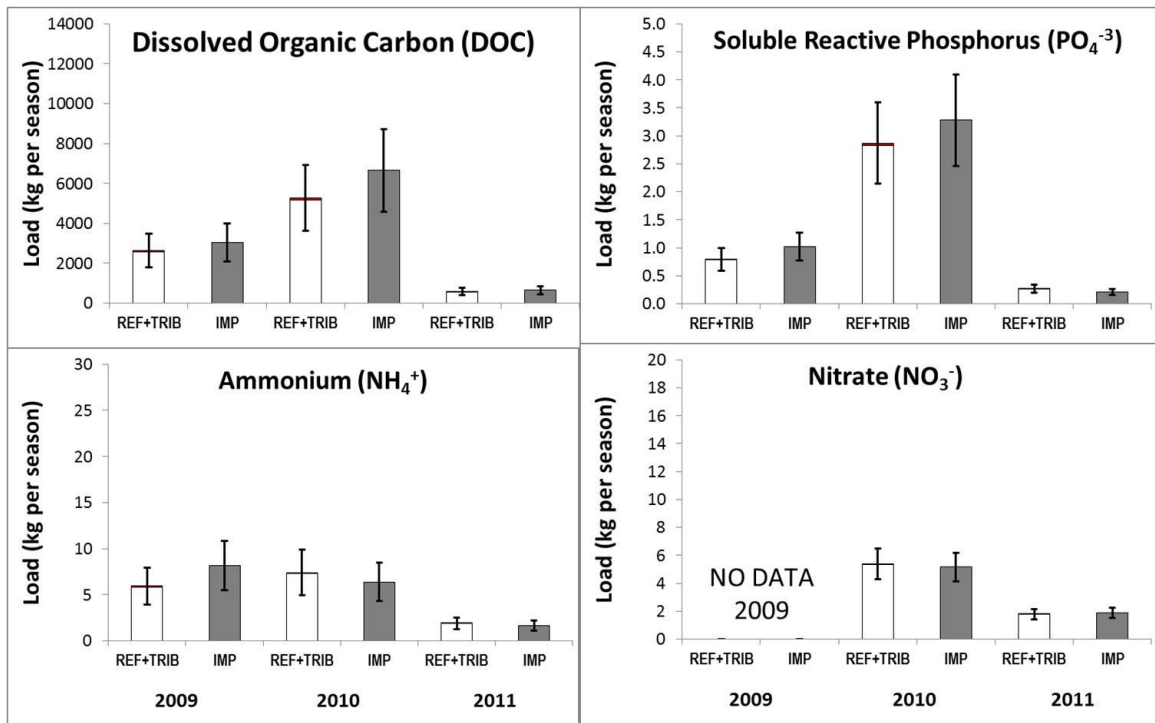


Figure 3. Cumulative seasonal load estimates for a suite of nutrients (DOC, SRP, NH₄⁺, NO₃⁻) for I-Minus2 for all three study seasons. Refer to legend in Figure 2. Cumulative seasonal load was calculated by multiplying the seasonal mean concentration of each nutrient for each sampling site (REF, IMP, TRIB) and multiplying by the daily mean discharge and summing all the days in the collection season (mid-June through mid-August). In the case of DOC, a relationship between DOC concentration and discharge was established and a unique load was predicted for each day within each season (i.e. LOADEST approach). Refer to Figure 1 for the site location labels. Error bars represent error propagation from sources of error as explained in Harmel et al. 2006.

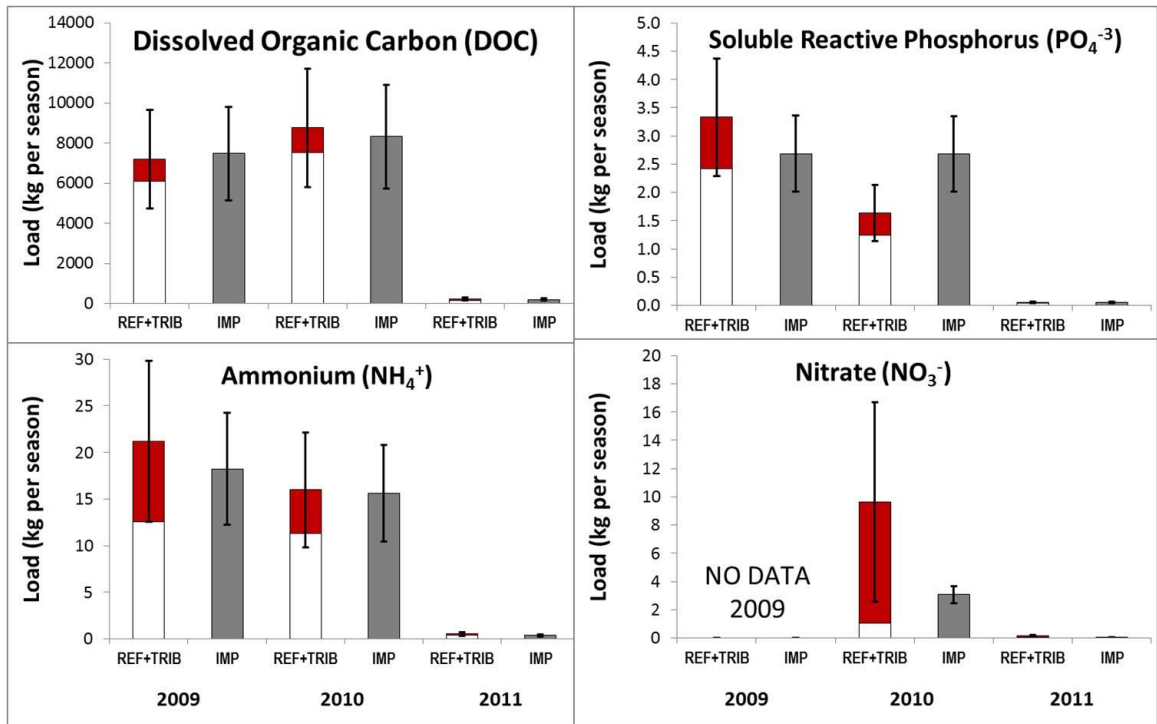


Figure 4. Cumulative seasonal load estimates for a suite of nutrients (DOC, SRP, NH₄⁺, NO₃⁻) for Toolik River for all three study seasons. Refer to legend in Figure 2. Cumulative seasonal load was calculated by multiplying the seasonal mean concentration of each nutrient for each sampling site (REF, IMP, TRIB) and multiplying by the daily mean discharge and summing all the days in the collection season (mid-June through mid-August). Refer to Figure 1 for the site location labels. Error bars represent error propagation from sources of error as explained in Harmel et al. 2006.

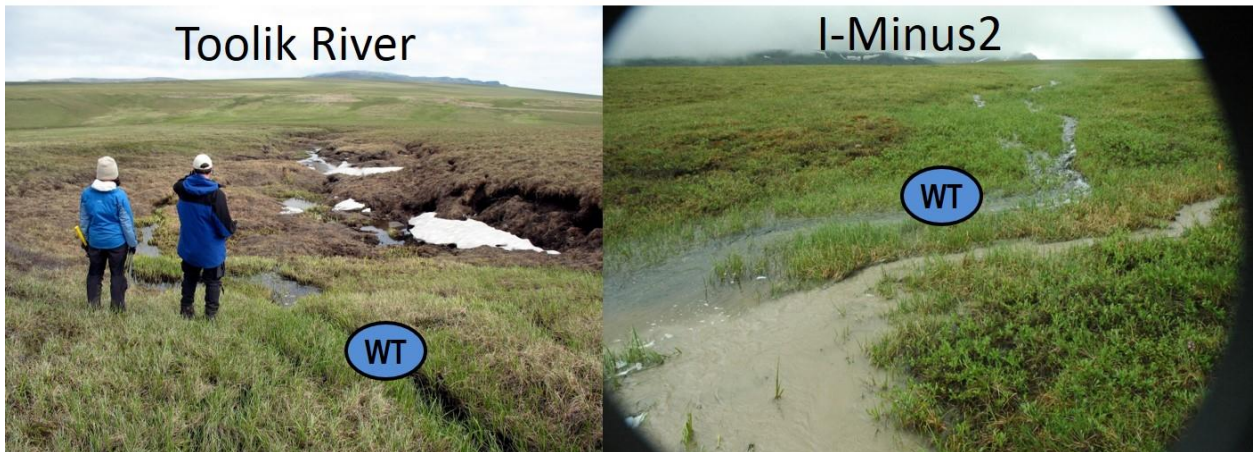


Figure 5. Visual comparison of the location of the water track at each gully site. The water track at the Toolik River site (left) was located above the headwall of the gully feature, whereas the

water track at the I-Minus2 site (right) was located adjacent to the feature and coincided with the thermokarst outflow below the gully.

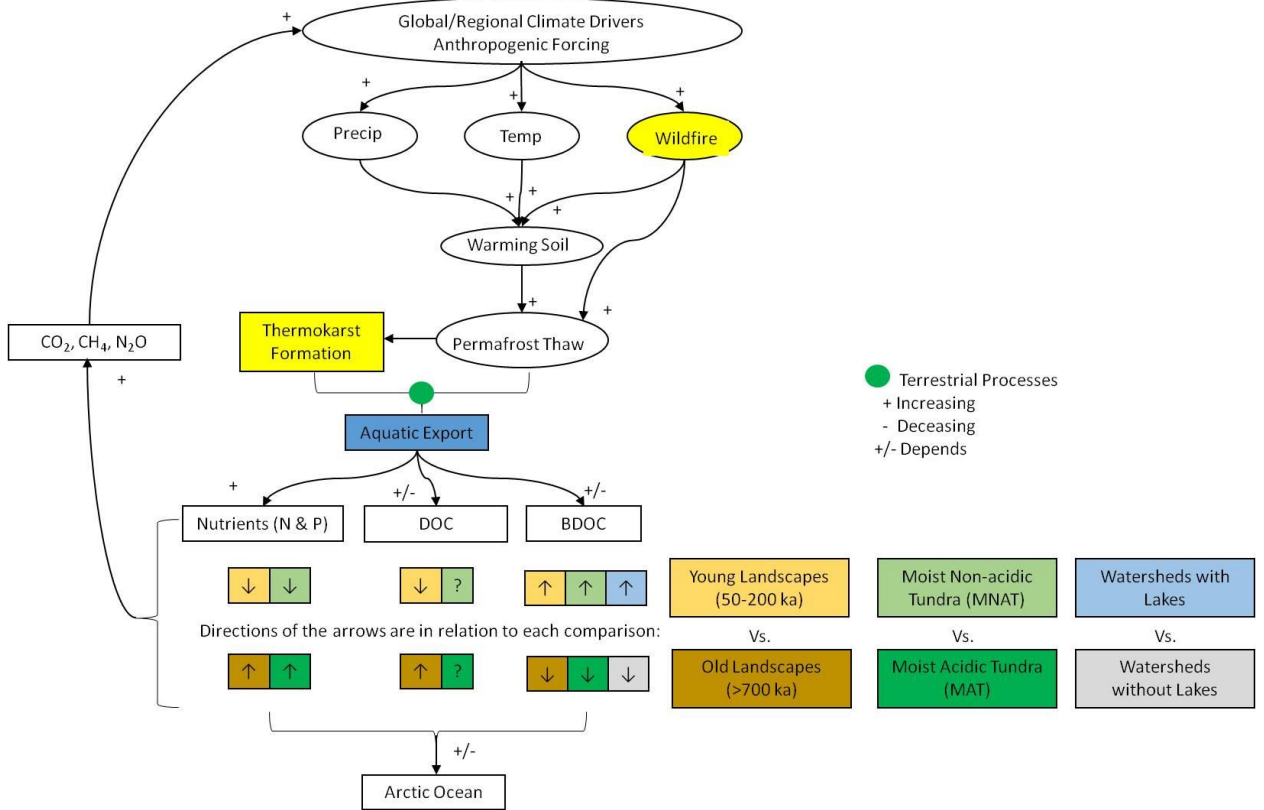


Figure 6. A conceptual model depicting the role of landscape characteristics with regard to the aquatic export of inorganic nutrients, dissolved organic carbon (DOC), and its biodegradability (BDOC) in response to permafrost thaw (via fire and/or thermokarst). Based on the findings from Chapter 4 and modified from Bowden (2010).

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APPENDIX A

A.1 Summary

This Appendix reports the findings from a series of thermokarst features and their receiving streams sampled in two regions of the Noatak National Preserve during 2010 and 2011 remote field campaigns. The intention of this effort was to ‘extensively’ sample features of differing morphologies and activity at a regional scale as a complement to the ‘intensively’ sampled sites near the Toolik Field Station (Chapters 2 and 3). Some of these features in the Noatak area were older, stabilized features while others sampled were young and actively exporting sediment to the receiving streams.

A.2 Site Descriptions

Wolf Creek (Kelly River 2010)

Wolf Creek is located at 67.734938 latitude and -161.403460 longitude, in the western edge of the Noatak National Preserve. It flows east to west and is characterized as a riffle/run/step stream in a narrow valley. The stream is impacted from the south side of the valley by several high-gradient active layer detachment slide thermokarsts that we believe initiated since 2006. The stream averages about 10cm in depth with a wetted width of about 3m. Substrates are characterized by small gravel and pebbles with some larger cobble of quartz, shale and some clay deposits. The impacted area of this stream is characterized by large peat mats and large deposits of fine sediment causing some ponding and braiding.

Cannon Creek (Kelly River 2010)

Cannon Creek is located in the western Noatak National Preserve at 67.863383 latitude and 161.480297 longitude. The stream lies in a narrow valley flowing west to east and is characterized by relatively higher gradients of riffle/pool/chute sequences. Substrates are bedrock, boulder and cobble with some epilithon. The reach is strongly shaded by dense, overhanging

alder. The thermokarst feature is a large active layer detachment slide that intersects the stream from the north. The thermokarst feature contains a large quantity of disturbed soil and peat that has created a distinct wall just a few meters from the stream. During rain events this feature probably supplies fine sediment to the stream.

Blood Slide Creek (Feniak Lake 2011)

Blood Slide Creek is located in the Feniak Lake region. A fresh, active-layer detachment slide was situated in the north-western edge of the watershed and its turbid outflow exported directly into Blood Slide Creek. An adjacent tributary, arising from the southern edge of the watershed served as a reference reach before its confluence with Blood Slide Creek. The two reaches are first-order, alluvial cobble-bottom headwater streams with relatively steep slopes.

Twin 1 and Twin 3 (Feniak Lake 2011)

Three large, active retrogressive thaw slumps impacted a segment of a relatively larger headwater stream in the Feniak Lake region. We sampled upstream and downstream of the first thaw slump (Twin 1) and the third thaw slump (Twin 3) as reference and impacted study reaches. Twin 1 and 3 are situated on a 2nd order and 3rd order alluvial, cobble-bottomed headwater stream, respectively.

A.3. Methods

Refer to the method sections in Chapter 2 and 3 of this dissertation.

A.4. Key Findings

A.4.1. Hydrochemistry and sediment

To determine changes in suspended sediment due to thermokarst inputs, we measured total suspended sediment (TSS) in Reference and Impacted reaches in the Noatak streams using standard methods. In the most active features sampled in the Noatak region, we observed elevated concentrations of TSS in the thermokarst outflow and in the downstream Impacted reaches (Table

4), but unable to test for significant differences due to low sample sizes. The stabilized features sampled in 2010 in the Noatak were not actively exporting high concentrations of sediment and were not hydrologically connected at the time of sampling. The outflow from active features sampled in the Feniak Lake region in 2011 contained very high concentrations of TSS and elevated the concentrations of the Impacted reaches in 2 out of the 3 receiving stream sites. Moreover, we visually observed the Feniak sites to be inundated with fine sediment in the upper portion of the Impacted reaches, immediately downstream of thermokarst outflows (see Figure 2).

Based on previous short-term experience, we expected that thermokarst disturbances would increase nutrient loading to arctic streams. There were distinct, elevated concentrations of nutrients from thermokarst outflow, but the signal appears to be lost in the Impacted reaches. We found that the water flowing out of thermokarst features (labeled *TK* in Tables 3 and 4) tended to have elevated concentrations of some nutrients in the more active features sampled in 2011: dissolved organic carbon (DOC); ammonium (NH₄-N); total dissolved nitrogen (TDN); and total dissolved phosphorus (TDP) (Table 4), all of which are important nutrients for aquatic primary producers and bacteria. Concentrations upstream and downstream of three active thermokarst slump features (Twins 1, 2 and 3) were not different even though slump outflow concentrations were quite high for all water quality metrics (Figure 4). Discharge measurements for the thermokarst outflow ranged from a mere 0.4 to 0.6 L s⁻¹ while the receiving stream discharge was ~222 L s⁻¹. Thus, the overall loading of from the thermokarst feature is very small relative to the total flux of nutrients in the receiving stream, which explains why we did not find large differences in concentrations between the upstream and downstream reaches. Although we observed a substantial amount of settled sediment in the Impacted reaches of the Twins receiving stream, the accumulation of sediment appeared to impacted only the upper regions of the study reach. Storm activity and high flows could potentially mobilize the sediment further downstream.

A.4.2. Benthic structure

Epilithic carbon and nitrogen standing stocks tended to be greater in Impacted reaches of the Feniak Lake region, although not significant. This observation is important as an indication that sediment and/or nutrient loading from thermokarst features may trigger a biological response in the biomass and function of primary producers and the composition of basal resources that supports the aquatic food web. The Impacted streams in the Noatak National Preserve tended to support lower concentrations (although not statistically significant) of algal biomass, suggesting that sediment loading may have interfered with photosynthesis of stream organisms.

A.4.3. Stream Metabolism

Whole-stream metabolism (WSM) is composed of Gross Ecosystem Production (GEP) and Ecosystem

Respiration (ER) and their difference is Net Ecosystem Production (NEP). Measurement of WSM relies on finely-resolved measurements of dissolved oxygen (DO), temperature, barometric pressure, light and discharge, at 5-min intervals. From this data we constructed an oxygen budget for our study stream reaches at Toolik River. GEP and ER in the Impacted reaches of Wolf and Canon tended to be lower and higher, respectively, compared to the Reference reaches (Figure 3). These results suggest that disturbance caused by thermokarst features may have lasting impacts on stream production and respiration

A.4.4. Nutrient spiraling

Nutrient spiraling metrics such as ambient nutrient uptake velocity (U_{amb}) and ambient nutrient uptake length (S_{w-amb}), were measured by a relatively new method of instantaneous nutrient tracer addition that has several advantages over earlier methods that are laborious and provide limited data. Refer to Table 6 for the results of SIEs conducted in the Kelly River region at Wolf Creek and Canon Creek in the Noatak National Preserve in 2010. No measureable uptake

of NO_3^- was observed in Wolf Creek or Canon Creek. Ambient nutrient concentrations during the SIE were similar between Reference and Impacted reaches, except that ambient NO_3^- concentration in the Impacted reach was nearly double that of the Reference at Canon Creek. Ambient uptake rates (U_{amb}) of NH_4^+ and PO_4^{3-} were generally greater in the Reference reaches compared to the Impacted reaches. Uptake lengths ($S_{w\text{-amb}}$) of NH_4^+ and PO_4^{3-} were at least twice as long in the Impacted reaches at both sites. Thermo-erosional features may have lasting impacts on stream nutrient uptake. Nutrient spiraling metrics such as ambient nutrient uptake velocity (U_{amb}) and ambient nutrient uptake length ($S_{w\text{-amb}}$), were measured by a relatively new method of instantaneous nutrient tracer addition that has several advantages over earlier methods that are laborious and provide limited data. There was no NO_3^- -N uptake measured in Wolf Creek and Cannon Creek. Both reference reaches showed higher areal uptake rates (U_{amb}) and lower uptake lengths (S_w) for both NH_4^+ -N and PO_4^{3-} -P (Table 6), suggesting that past sediment inputs from thermokarst disturbance may have interfered with the uptake of key inorganic nutrients by the biota. Differences in rates of metabolism metrics for the dates in which solute injection experiments were conducted were consistent with areal uptake rates (i.e. the reaches with the greater uptake rates, also exhibited higher rates of GEP). These results are consistent with those measured in thermokarst impacted streams on the North Slope, AK (Chapter 2).

Table 1. Study sites in the Noatak National Preserve, Alaska, 2010 and 2011.

Site Name	Latitude (DD)	Longitude (DD)	Date Sampled (dd-mm-yyyy)	Watershed Area (km ²)	Reach (m)	Reach Depth (cm)	Reach Width (m)	Disturbance Type
Wolf Creek Reference	67.73768	-161.41554	28-Jul-10	3.21	320	12.1	1.5	Reference
Wolf Creek Impacted	67.72905	-161.42448	28-Jul-10	~3.21	380	9.9	3.6	ALD
Cannon Creek Reference	67.86358	-161.47821	2-Aug-10	2.46	340	11.0	2.9	Reference
Cannon Creek Impacted	67.86601	-161.47829	2-Aug-10	~2.46	320	15.1	2.1	ALD
Bloodslide Creek Reference	68.24727	-156.95110	25-Jul-11	3.02	200	17.8	2.4	Reference
Bloodslide Creek Impacted	68.28087	-157.02447	25-Jul-11	5.23	200	8.1	3.1	ALD
Bloodslide Creek Recovery	68.27943	-157.02560	30-Jul-11	1.54	200	8.5	1.5	recovered ALD
Woodpile Reference	67.90142	-156.49367	26-Jul-11	65.00	200	-	-	Reference
Woodpile Impacted	67.89605	-156.50733	26-Jul-11	~65.00	200	-	-	Thaw Slump
Twin 1 Reference	67.96198	-156.78135	27-Jul-11	23.19	300	11.9	8.3	Reference
Twin 1 Impacted	67.96252	-156.79237	27-Jul-11	~23.19	300	11.4	9.7	Thaw Slump
Twin 3 Recovery	67.96120	-156.83042	28-Jul-11	43.05	300	14.1	12.0	Reference
Twin 3 Impacted	67.95703	-156.83345	28-Jul-11	~43.05	300	15.9	13.7	Thaw Slump

Table 2. Sampling efforts during the campaigns in the Noatak National Preserve, Alaska.

Sampling	Purpose
Geomorphic survey (2010 and 2011)	To characterize geomorphic characteristics of each reach
Grab water sampling (2010 and 2011)	To characterize the chemistry of reference and impacted reaches and the gully drainage water
Solute Injection Experiments (2010)	To estimate nutrient uptake dynamics
Whole-stream metabolism (2010)	To estimate ecosystem production and respiration
Epilithic rock scrubs (2010 and 2011)	To characterize the benthic communities (algal biomass via chlorophyll-a, particulate elements)

Table 3. Water quality metrics from sites sampled in the Kelly River region of the Noatak National Preserve in 2010. REF = reference stream reach, upstream of TK outflow; TK = thermokarst outflow; IMP = impacted stream reach, downstream of TK outflow.

	Stabilizing 2010 (Was active in 2007)					
	Wolf Creek			Cannon Creek		
	<i>REF</i>	<i>TK</i>	<i>IMP</i>	<i>REF</i>	<i>TK</i>	<i>IMP</i>
T (°C)	8.0	7.7	8.0	7.9	nd	7.1
Conductivity (uS/cm)	429	406	398	207	nd	212
pH	8.19	8.31	8.3	8.0	nd	8.1
Alkalinity (ueqL)	2794	4009	2842	1527	1507	1526
DOC (uM)	335	555	482	516	620	594
NH ₄ ⁺ -N (ug/L)	3.00	-	1.40	9.70	-	9.50
PO ₄ ⁻ -P (ug/L)	7.20	-	4.50	5.00	-	4.80
NO ₃ ⁻ -N (ug/L)	19.2	-	15.5	6.7	-	12.6
TDN (uM)	11.4	16.1	15.0	15.0	18.7	17.9
TDP (uM)	-	-	-	-	-	-
TSS (mg/L)	3.1	7.3	4.7	3.2	0.0	1.8

Table 4. Water quality metrics from sites sampled in the Feniak Lake region of the Noatak National Preserve in 2011. REF = reference stream reach, upstream of TK outflow; TK = thermokarst outflow; IMP = impacted stream reach, downstream of TK outflow

	Fresh and Active in 2010											
	BloodSlide Creek			Wood Pile			Twin I			Twin III		
	REF	TK	IMP	REF	TK	IMP	REF	TK	IMP	REF	TK	IMP
T (°C)	12.8	11.7	13.3	9.3	-	9.7	-	18.8	11.2	14	19	11.5
Conductivity (uS/cm)	161	302	203	91.3	-	98.7	113	563	129	177	974	181
pH	7.7	7.9	8.1	7.9	-	8	8.1	8.5	8.1	8.1	8.6	8.3
Alkalinity (ueq/L)	1282	3184	2176	650	-	706	656	4281	834	1364	3514	1406
DOC (uM)	242	229	138	193	353	190	220	1338	221	234	1551	223
NH ₄ ⁺ -N (ug/L)	6.34	1.31	0.61	1.07	1.70	1.25	0.69	42.91	0.48	0.54	8.85	1.04
PO ₄ ⁻ P (ug/L)	0.15	0.38	0.11	0.10	0.01	0.11	0.14	0.08	0.10	0.10	0.13	0.11
NO ₃ ⁻ -N (ug/L)	0.4	0.3	3.0	1.3	5.4	1.4	4.9	12.3	4.9	4.6	1.3	5.0
TDN (uM)	8.9	8.4	8.4	7.6	31.1	7.2	12.3	94.2	11.3	12.1	81.0	12.2
TDP (uM)	0.09	2.39	-	0.05	-	-	0.05	-	0.09	0.04	0.66	0.05
TSS (mg/L)	0.7	122.1	47.5	-	-	-	0.2	39973	139.6	15.5	2720	7.7

Table 5. Epilithic chlorophyll-*a*, standing stocks and molar ratios of epilithic carbon, nitrogen and phosphorus from rocks in the Reference and thermokarst-Impacted reaches of Noatak streams. Means (mean of 4 individual rock scrubs per stream reach), sample size (n = single reach), and 1 standard error (SE) are reported. No statistical comparisons were made due to low sample sizes.

Riffle Rocks	Chlorophyll- <i>a</i>	Standing Stocks ($\mu\text{mol}/\text{cm}^2$)			Molar Ratios			
	($\mu\text{g}/\text{cm}^2$)	Carbon	Nitrogen	Phosphorus	C:N	C:P	N:P	
Kelly River 2010	Reference (n=2)	0.24 (0.05)	10.5 (1.5)	1.72 (0.14)	0.10 (0.01)	6.03 (0.59)	116 (23)	18.8 (2.5)
	Impacted (n=2)	0.19 (0.03)	12.8 (2.1)	1.65 (0.22)	0.11 (0.01)	6.93 (0.72)	126 (20)	16.5 (2.3)
Feniak 2011	Reference (n=3)	0.67 (0.20)	27.1 (8.4)	2.74 (0.86)	0.16 (0.01)	10.7 (0.9)	162 (40)	16.6 (4.0)
	Impacted (n=4)	0.43 (0.08)	41.4 (6.2)	5.21 (2.50)	0.21 (0.02)	14.2 (2.0)	254 (64)	36.6 (17.6)
	Recovery (n=3)	0.79 (0.30)	35.4 (9.2)	2.04 (0.41)	0.11 (0.01)	12.5 (0.9)	418 (93)	31.5 (7.7)

Table 6. Nutrient spiraling metrics for solute injection experiment (SIE) dates conducted in 2010 at Wolf Creek and Cannon Creek in 2010. S_{w-amb} = uptake length; U_{amb} = total areal uptake rate; $Nutrient_{amb}$ = ambient nutrient concentration; GEP = Gross Ecosystem Production; ER = Ecosystem Respiration; and NEP = Net Ecosystem Production.

	Wolf Creek		Cannon Creek	
	7/28/2010		7/29/2010	
	Reference	Impacted	Reference	Impacted
<i>Nutrient Spiraling Metrics</i>				
NO₃-N				
S_{w-amb} (m)	-	-	-	-
U_{amb} ($\mu\text{g m}^{-2} \text{min}^{-1}$)	no uptake	no uptake	no uptake	no uptake
$\text{NO}_3\text{-N}_{amb}$ ($\mu\text{g L}^{-1}$)	19.2	15.5	6.7	12.6
NH₄-N				
S_{w-amb} (m)	370	748	120	513
U_{amb} ($\mu\text{g m}^{-2} \text{min}^{-1}$)	16.3	3.9	161	37.1
$\text{NH}_4\text{-N}_{amb}$ ($\mu\text{g L}^{-1}$)	3	1.4	9.7	9.5
PO₄-P				
S_{w-amb} (m)	60.1	139	85.5	275
U_{amb} ($\mu\text{g m}^{-2} \text{min}^{-1}$)	238	64.5	117	35.1
$\text{PO}_4\text{-P}_{amb}$ ($\mu\text{g L}^{-1}$)	7.2	4.5	5	4.8
<i>Metabolism Metrics</i>				
GEP ($\text{g O}_2 \text{m}^{-2} \text{day}^{-1}$)	1.5	1.0	2.2	1.8
ER ($\text{g O}_2 \text{m}^{-2} \text{day}^{-1}$)	-17.8	-18.0	-19.8	-22.4
NEP ($\text{g O}_2 \text{m}^{-2} \text{day}^{-1}$)	-16.4	-17.0	-17.6	-20.6

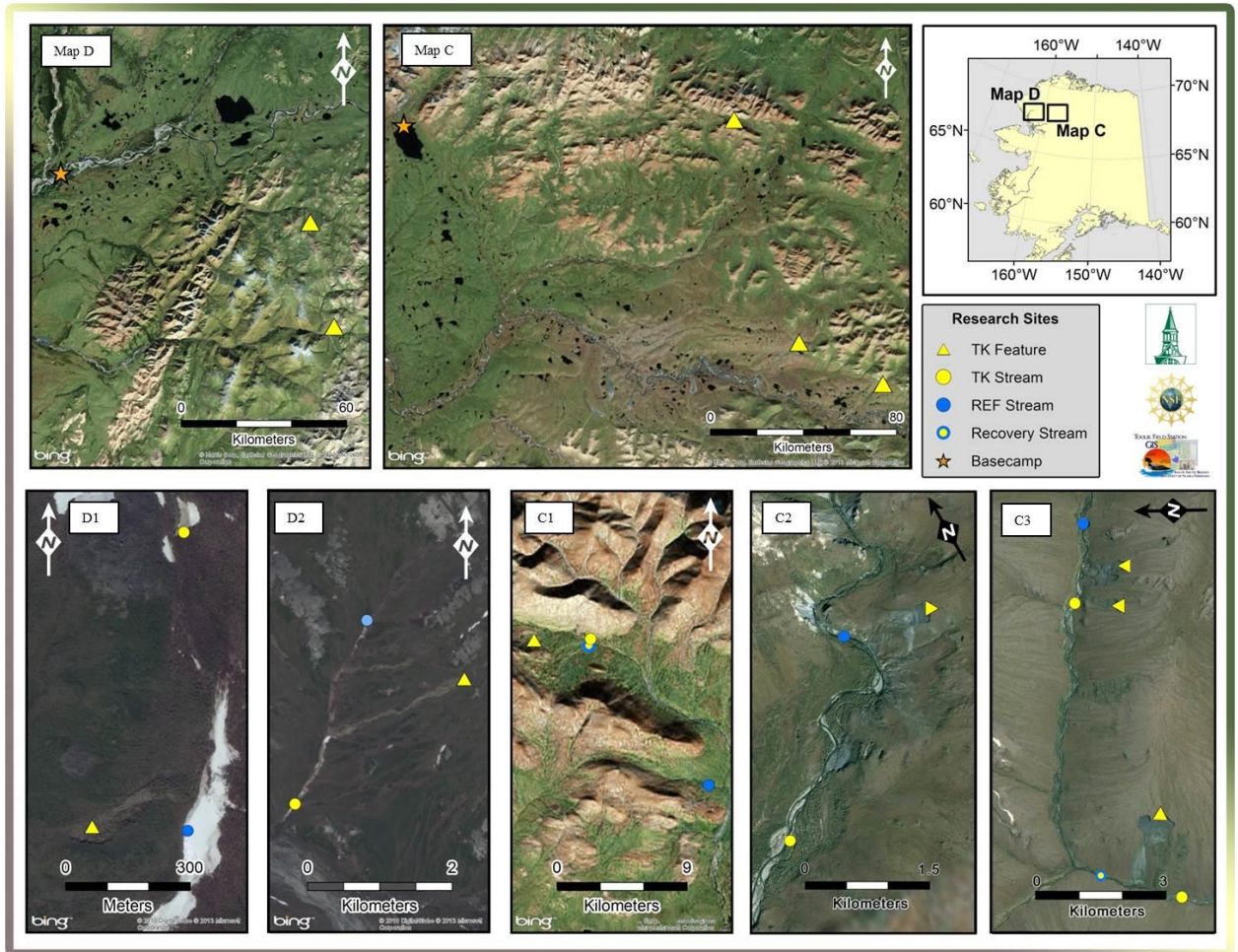


Figure 2. Study sites in the Noatak National Preserve. Map D) Kelly River region was sampled in 2010 and includes 2 stream sites: D1) Wolf Creek and D2) Cannon Creek, both impacted by older, recovered active-layer detachment slides. Map C) Feniak Lake region was sampled in 2011 and includes 4 stream sites: C1) Blood Slide Creek; C2) Wood Pile Creek; and C3) Twin 1, 2, and 3. Map Credit: R. Fulweber, Toolik Field Station GIS and Remote Sensing Facility.

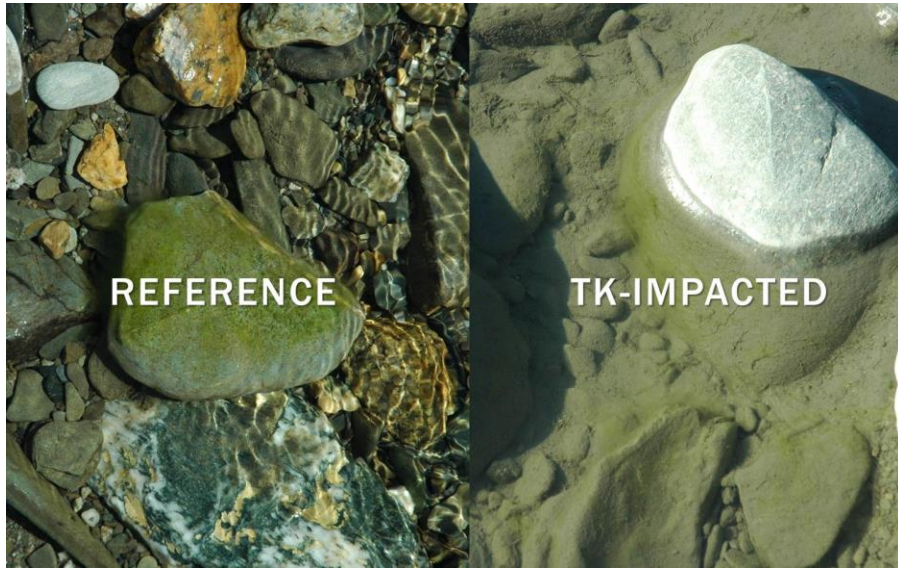


Figure 3. Stream substrate visual from the Twin 1 Reference and Impacted reaches (photo credit: M. Flinn).

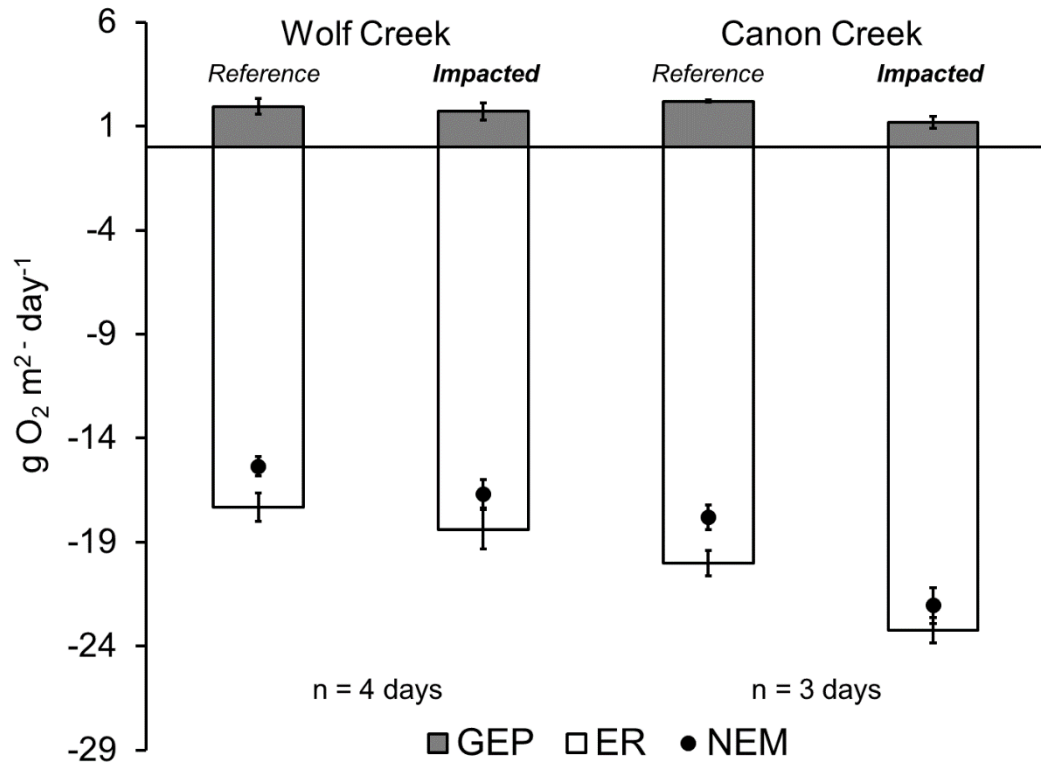


Figure 4. Mean and standard error of whole-stream metabolism metrics: gross ecosystem productivity (GEP), ecosystem respiration (ER), and net ecosystem productivity (NEP) of for the Noatak 2010 Reference and Impacted reaches. No statistical comparisons were made due to low sample sizes.

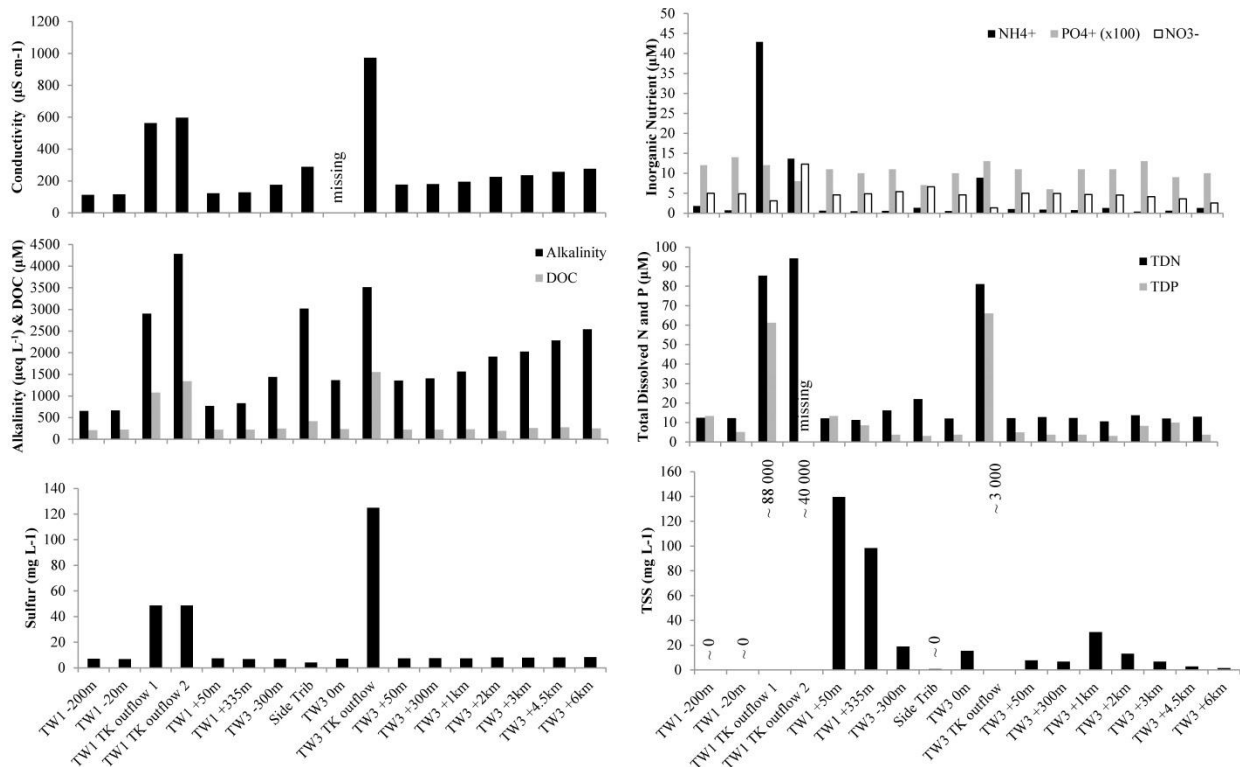


Figure 5. A survey of the Twins (1 and 3) (see Figure 1 Map C3 inset) thaw slump features located in the Feniak area of the Noatak National Preserve. The ‘-’ indicates the upstream/reference reach and meter (m) location along the reach; the ‘+’ indicates the downstream/impacted reach and meter (m) location along the reach; ‘TK outflow’ represents the water flowing from the hillslope and thermokarst feature directly before entering the receiving stream; ‘Side Trib’ represents the tributary entering from the north; the impacted stream was sampled at kilometer (km) increments downstream.