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3 1 **The Arctic in the 21<sup>st</sup> century: Changing biogeochemical linkages across a**  
4 2 **paraglacial landscape of Greenland**  
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Draft Manuscript

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3 16 **Abstract**

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5 18 The Kangerlussuaq area of southwest Greenland encompasses diverse ecological,  
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7 19 geomorphic and climate gradients that function over a range of spatial and temporal scales.  
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9 20 Ecosystems range from the microbial communities on the ice sheet, through moisture stressed  
10 21 terrestrial vegetation (and their associated herbivores) to freshwater and oligosaline lakes.  
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12 22 These ecosystems are linked by a dynamic glacio-fluvial-aeolian geomorphic system that  
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14 23 transports water, minerogenic material, organic carbon and nutrients from the glacier surface  
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16 24 to adjacent terrestrial and aquatic systems. This paraglacial system is now subject to  
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18 25 substantial change due to rapid regional warming since 2000. Here we describe changes in  
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20 26 the eco- and geomorphic systems at a range of timescales, and explore rapid future change in  
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22 27 the links that integrate these systems. We highlight the importance of cross-system subsidies  
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24 28 at the landscape scale and importantly, how these might change in the near future as the  
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26 29 Arctic is expected to continue to warm.  
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3 33 **Arctic ecosystems have undergone major changes over the past century.** Much of this  
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5 34 change is driven by higher temperatures, a warming that is enhanced relative to lower  
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7 35 latitudes but other stressors, notably atmospheric deposition of reactive nitrogen and other  
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9 36 pollutants, also have profound ecological effects. Much of the focus in arctic geomorphic and  
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11 37 ecological research has been on the response of individual units (e.g., floodplain, population,  
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13 38 community) to climate and atmospheric changes. Many of the ecological responses have been  
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15 39 relatively predictable in terms of our understanding of the underlying processes, i.e. altered  
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17 40 phenology, longer growing seasons, greening (i.e. increased plant biomass) of terrestrial  
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19 41 ecosystems, range expansion or contraction of plants and animals, and altered soil microbial  
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21 42 activity associated with deepening active layers.  
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25 43 In the broader ecological literature, the importance of climate-driven alterations to  
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27 44 connections across ecosystems is increasingly recognized (Greig et al. 2012). Resources such  
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29 45 as carbon, nutrients, and water are exchanged across ecosystems, and the exchange of these  
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31 46 “subsidies” can be tightly coupled (Nakano & Murakami 2001), raising the need to better  
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33 47 understand the pools and their linkages across the landscape. In the Arctic, much of the focus  
34  
35 48 on cross-system connections has been on one-way delivery of water, carbon and nutrients  
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37 49 from glaciers to rivers to marine systems (Hawkings et al. 2015, O’Neel et al. 2015). The  
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39 50 linkages across continental systems (glacier, terrestrial, freshwater), as well as the myriad  
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41 51 feedbacks among them, are much less clear, despite their likely importance in shaping how  
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43 52 the landscape responds to climate and atmospheric deposition.  
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47 53 In the Arctic, glaciated landscapes provide model systems in which to explore the  
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49 54 complexity of cross-system physical and biogeochemical linkages. The past and present  
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51 55 influences of glaciers impart signature effects on northern landscapes, layered on top of  
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53 56 typical arctic features (e.g., permafrost). Active glaciers produce rock flour and provide an  
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55 57 important biogeochemical interface with the atmosphere, concentrating and storing water,  
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3 58 carbon, nutrients and pollutants. These materials are released into the proglacial floodplain, a  
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5 59 key feature of the associated paraglacial landscape (defined as a landscape that is directly  
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7 60 conditioned by former glaciation and deglaciation). These floodplains are major components  
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9 61 of the geomorphic system that couple glaciers and ice sheets to wider sedimentary  
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11 62 environments (Bullard 2013). They provide sediments that are transported by fluvial and  
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13 63 aeolian processes within the landscape at a range of timescales. In turn, the aeolian dispersal  
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15 64 of dust from these floodplains delivers nutrient subsidies to terrestrial and freshwater systems  
16  
17 65 as well as back to the glacier itself. These systems provide complex but rich opportunities in  
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19 66 which to assess physical and biogeochemical linkages and feedbacks across arctic landscapes,  
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21 67 and how these may change in the future.  
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25 68 The Arctic has witnessed some of the most rapid, non-linear environmental change in  
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27 69 the last 20 years, with perhaps the best example of this being Greenland, where mean annual  
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29 70 air temperatures between 2007-2012 were 3°C higher than averages from 1979-2000  
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31 71 (Mayewski et al. 2014). Greenland Ice Sheet (GrIS) mass losses are more than 100% higher  
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33 72 post-1996 compared to the period between 1958-1996 (van den Broeke et al. 2009), with an  
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35 73 extreme melt event on the GrIS in 2012 (e.g., Hanna et al. 2014). During the last decade, the  
36  
37 74 North Atlantic and Arctic oceans have experienced the most drastic loss of sea ice ever  
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39 75 recorded (Parkinson and Comiso 2013), coinciding with regional increases in marine net  
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41 76 primary production. Sulfur deposition products originating from marine phytoplankton have  
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43 77 increased with these changes in sea ice (Sharma et al. 2012). Collectively, it is quite apparent  
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45 78 that in the 21<sup>st</sup> century, we have entered a period of rapid environmental change in the Arctic.  
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49 79 Here we synthesize research from the area around Kangerlussuaq, southwest  
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51 80 Greenland, at a range of temporal and spatial scales in a cross-system, multidisciplinary  
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53 81 approach. The area of focus spans from the margin of the GrIS to the associated paraglacial  
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55 82 landscape, situated in the largest ice-free margin of the country (figure 1). Our goal is to  
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83 begin to delineate the resource pools and cross-system connections in this region to enable  
84 greater understanding of future climate-driven changes to this region.

### 85 **Kangerlussuaq: the Arctic and global change encapsulated**

86 The area along Kangerlussuaq (Søndre Strømfjord in Danish) encapsulates the Arctic in a  
87 ~150 km (~6000 km<sup>2</sup>) corridor from the ice sheet itself to the valley and cirque glaciers at the  
88 coast. This land mass spanning from the ice sheet margin to the coast of the Labrador Sea  
89 includes a range of landscapes and  
90 ecosystems (figures 2, 3): freshly  
91 exposed moraines; large outwash  
92 plains (sandurs); terrestrial  
93 ecosystems that include dwarf shrub  
94 tundra, steppe and snow-bed  
95 communities; lakes and ponds that  
96 range from organic rich and shallow  
97 to dilute and deep to oligosaline and  
98 meromictic. Streams range from  
99 turbid silt laden rivers draining the ice  
100 sheet to oligotrophic and fast flowing  
101 in the coastal mountains.

#### **Box 1. Terms and definitions**

**Aeolian:** relating to or arising from the action of wind

**Cryoconite:** dust made of small rock particles, soot, and microbes that is found on the surface of a glacier, especially on the bottom of small depressions; causes darkening of ice surfaces

**Fluvial:** of or found in a river

**Jökulhlaup:** a type of glacial outburst flood

**Loess:** previously deposited and biologically-transformed dust

**Moulin:** a nearly vertical shaft in a glacier, formed by surface water percolating through a crack in the ice

**Paraglacial:** referring to surface processes and landscapes directly conditioned by former glaciation and deglaciation

**Periglacial:** the zone peripheral to glaciers

**Sandur:** outwash plain formed by meltwater from glaciers

**Talik:** region of unfrozen soil or bedrock beneath a lake

102 The Kangerlussuaq area is located in the continuous permafrost zone, but permafrost  
103 conditions vary considerably in the region. Recent borehole measurements and active layer  
104 probing show that active layer thickness varies from approximately 30 cm in an ice-wedge  
105 polygon affected peat bog at 430 m a.s.l. near the GrIS margin (Ingeman-Nielsen et al. 2012),  
106 to at least 1.8 m in a glaciomarine silty clay deposit at Kangerlussuaq airport (Christiansen et  
107 al. 2010). As well as strong local and regional spatial climate and vegetation gradients along

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108 Kangerlussuaq, there are also pollutant gradients that reflect rainfall differences as well as  
109 ice marginal dynamics. For example, pollution mercury inventories are nearly 3-fold higher  
110 in lakes close to the ice sheet margin compared to the coast (Bindler et al. 2001).

111 At Kangerlussuaq airport, the mean annual air temperature (MAAT) was  $-5.0\text{ }^{\circ}\text{C}$  and  
112  $-3.9\text{ }^{\circ}\text{C}$  for the periods 1974-2012 and 2001-2012, respectively (Mernild et al. 2014). This  
113 recent increase in local MAAT (figure 4) is consistent with the MAAT increase observed in  
114 Greenlandic coastal synoptic meteorological stations (Hanna et al. 2012), the increasing  
115 frequency of warm air temperature extremes (Mernild et al. 2014), and the recent occurrence  
116 of extreme melt events in 2010 and 2012 (Tedesco et al. 2011, Hanna et al. 2014). The mean  
117 annual precipitation (MAP) at Kangerlussuaq airport was 242 mm (1981-2012), showing an  
118 insignificant increase in MAP to 258 mm in recent years (2001-2012; Mernild et al. 2015)  
119 although there has been a change in seasonality. Model simulations based on down-scaling of  
120 the regional climate model HIRHAM4 coupled with the general circulation model ECHAM5  
121 indicate that from 1950 to 2080 the MAAT and MAP will increase by  $3.4\text{ }^{\circ}\text{C}$  and 95 mm,  
122 respectively (Mernild et al. 2011).

### 123 **Recent changes within regional landscape geomorphic and ecological** 124 **systems**

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126 **Glacier** The ice sheet margin at Kangerlussuaq has recently experienced a period of  
127 thickening (1980-2000), followed by rapid ice-marginal thinning and recession of outlet  
128 glaciers (Knight et al. 2007). Two of the most prominent glacier changes have been the  
129 evolution of supraglacial lakes and the reoccurrence of drainage outbursts from a large ice-  
130 dammed lake. The number of supraglacial lakes along this part of the western GrIS margin  
131 has increased, and almost 30% of the lakes appear to drain in a few days (Fitzpatrick et al.  
132 2014). The supraglacial lakes drain into moulins, which then discharge meltwater to the  
133 terminus of the ice sheet, which can contribute to ice marginal lakes. A  $\sim 1\text{ km}^2$  ice-dammed  
134 lake on the northern flank of Russell Glacier (figure 2d) is known to have drained repeatedly

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3 135 from the late 1940s until 1987. After 20 years of lake level stability due to increased  
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5 136 thickness of the ice sheet margin, a jökulhlaup (rapid drainage of ice-dammed lakes) in 2007  
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7 137 marked a renewed cycle of flooding (e.g., Russell et al. 2011). Jökulhlaup events have  
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9 138 resulted in downstream floods almost every year since 2007 during the late summer. Also,  
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11 139 intense ice sheet melt in July 2012 caused the Watson River to rapidly reach the highest level  
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13 140 ever recorded since records began in the 1940s. Both types of glacier floods affect  
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15 141 downstream proglacial geomorphology, sedimentary systems and biological communities at  
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17 142 Kangerlussuaq (e.g., Carrivick et al. 2013). In brief, these geomorphological impacts include  
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19 143 delta formation into lakes, channel bank erosion, channel bedrock incision, and sediment  
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21 144 deposition in terrestrial and lacustrine basins and into the fjord.  
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23 145 **Terrestrial** Since observational monitoring of plant phenology in Kangerlussuaq began in  
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25 146 1993, the start of the plant growing season has advanced by approximately 20 days (Kerby &  
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27 147 Post 2013, Post 2013). Phenological advancement has varied considerably among plant  
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29 148 species, with graminoids and early-emergent forbs displaying the greatest advancement, and  
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31 149 deciduous shrubs the least pronounced advancement, in the timing of spring green-up.  
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33 150 Despite slower rates of phenological advance, canopy cover of the two dominant species of  
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35 151 deciduous shrubs, *Betula nana* and *Salix glauca*, has increased near Kangerlussuaq,  
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37 152 ostensibly in relation to local warming (Post et al. 2013). Plot-scale CO<sub>2</sub> flux measurements  
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39 153 indicate that such increases have the potential to substantially increase ecosystem carbon  
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41 154 uptake (Cahoon et al. 2012). Increases in deciduous shrub cover in the area may, however, be  
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43 155 checked on occasion by outbreaks of the caterpillar larvae of a noctuid moth, *Eurois occulta*,  
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45 156 of which there have been two since 2002 (Avery and Post 2013). Such outbreaks may  
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47 157 increase in severity in the Kangerlussuaq region and other parts of the Arctic with future  
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49 158 warming.  
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3 159 Animal populations have also changed in recent decades. Daily censuses of the two  
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5 160 resident species of large herbivores inhabiting the area, caribou (*Rangifer tarandus*) and  
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7 161 muskoxen (*Ovibos moschatus*), have been conducted annually throughout the reproductive  
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9 162 seasons of both species at a long-term study site 25 km east of Kangerlussuaq (Post 2013).  
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11 163 These counts indicate that the annual maximum number of caribou observed at that site have  
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13 164 declined from a peak of nearly 600 in 2006 to 119 in 2015, while the annual maximum  
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15 165 number of muskoxen has fluctuated between approximately 15 and 50 and may be increasing  
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17 166 slowly. The endemic Greenland White-fronted Goose *Anser albifrons flavirostris* has been  
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19 167 declining since peaking at 35,600 in 1999 (Stroud et al. 2012), while the Canada Goose  
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21 168 *Branta canadensis interior* has probably been breeding in West Greenland since at least  
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23 169 1863, but has increased in range and abundance in recent years, reaching over 500 in recent  
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25 170 years (Fox & Glahder 2010).

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29 171 **Aquatic** Limnological surveys were initiated in 1996 (Anderson et al. 2001), prior to the  
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31 172 recorded onset of regional warming and since then there have been a number of systematic  
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33 173 changes. Like the majority of arctic lakes, those around Kangerlussuaq are nutrient poor (TP  
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35 174  $<7 \mu\text{g l}^{-1}$ ; TN ranges  $300\text{--}800 \mu\text{g l}^{-1}$ ) (Whiteford et al. 2016) but are major C stores at the  
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37 175 landscape scale (Anderson et al. 2009). Nitrate is often low with the exception of the coastal  
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39 176 lakes where it is notably higher in the spring from a strong N-pulse derived from melting  
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41 177 snow pack. Stable isotope analyses of this  $\text{NO}_3$  suggest it is enhanced by atmospherically-  
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43 178 derived reactive N deposition. The spatial gradient in nutrients and their seasonal availability  
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45 179 results in pronounced patterns in nutrient limitation (Whiteford et al. 2016).

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49 180 Another notable change is the increasing lake levels in a number of the oligosaline  
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51 181 lakes at the head of the fjord where lake levels have increased by up to 2.5 m over the last 12  
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53 182 years as evidenced by drowned shrub tundra along the lake shores. Many of the inland lakes  
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55 183 have high dissolved organic carbon (DOC) concentrations ( $\sim 40\text{--}100 \text{ mg l}^{-1}$ ) due to the long  
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3 184 retention times and evapoconcentration over centuries (Anderson and Stedmon 2007).  
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5 185 Regional declines have been observed in DOC (by 60%) in a number of freshwater lakes in  
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7 186 the period 2000–2014 (Saros et al. 2015); there have also been increases in sulfate but not  
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9 187 conductivity or chloride. This decline in the DOC pool coupled with recent decreases in C  
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11 188 burial rates in this area suggests major changes in C cycling over recent years. Moreover, the  
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13 189 change in DOC concentration coupled with rising air temperatures will change thermal  
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15 190 stratification patterns with associated implications for primary production (Saros et al. 2015).  
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### 18 191 **Linkages across a paraglacial landscape**

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20 192 The complex interactions between the GrIS and adjacent ecosystems are not immediately  
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22 193 apparent given their well delineated boundaries (ice, water, tundra) and despite their  
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24 194 proximity; it is possible to transition from arctic steppe/tundra to glacial ice in meters (figure  
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26 195 2c). Moreover, although there is considerable hydrological discharge from the GrIS annually  
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28 196 there is a hydrological disconnect between the ice sheet and adjacent terrestrial ecosystems  
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30 197 (figure 5). Similarly, the low annual precipitation and the presence of continuous permafrost  
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32 198 suggest that hydrological linkages between tundra soils and aquatic ecosystems are presently  
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34 199 limited. Synthesizing research in the Kangerlussuaq area over the last two decades, however,  
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36 200 highlights the complex interactions between glaciology, the terrestrial geomorphic system  
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38 201 and terrestrial ecosystems (both tundra and limnic). These interactions operate at a range of  
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40 202 ecological/organismal (microbes to reindeer) and spatial (e.g., migration of the Greenland  
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42 203 White-fronted Goose from Greenland to the British Isles and of Canada Geese to North  
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44 204 America) and temporal scales (seasonal C fixation by microbes on the ice sheet to long-term  
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46 205 C sequestration by lakes). Here we highlight some of the major interactions.  
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51 206       Seasonal melt events and jökulhlaups that cause widespread flooding deposit fine  
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53 207 (<2000  $\mu\text{m}$ ) sediments across the sandur. Following recession of the water, these deposits  
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55 208 desiccate rapidly. Strong winds can entrain the sediments causing dust storms and forming  
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3 209 localised dunefields, effectively linking the glaciofluvial and aeolian systems (figures 3 and  
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5 210 5). Bullard & Austin (2011) described rapid deflation of jökulhlaup deposits leading to  
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7 211 intense dust storms in the valley. There are no year round measurements of modern aeolian  
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9 212 flux or deposition rates for the region, but process studies of dust flux on the sandur suggest  
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11 213 summer transport rates of up to 0.082 grams per meter width per second ( $\text{g m w s}^{-1}$ ) (Bullard  
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13 214 & Austin 2011).

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16 215 Dust storms can reach several hundred meters above the sandur plain (figure 3d). Dust  
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18 216 deposited on the surface of the ice sheet ablation zone preferentially absorbs solar radiation,  
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20 217 and melts down into the ice surface. These debris accumulations may be concentrated (in  
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22 218 cryoconite holes) or dispersed (as ‘dirty ice’ or ice algae (Yallop et al. 2012)), but are  
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24 219 biological ‘hot spots’ on an otherwise inhospitable glacier surface. Recent surveys highlight  
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26 220 the sheer scale of active photosynthetic microbial communities in cryoconite holes (Yallop et  
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28 221 al. 2012). Meltwater flushes through the ice algae and debris, initially in small, interlinked  
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30 222 water veins and eventually in supraglacial streams that lead to supraglacial lakes or moulins.

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34 223 Aeolian material is also deposited on soils and directly into lakes across the region.  
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36 224 Modern dust deposition rates in lake catchments above the floodplain are around  $70 \text{ g m}^{-2} \text{ yr}^{-1}$   
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38 225 (Willemse et al. 2003). Evidence of the persistence of this process in the past can be found in  
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40 226 lake (Anderson et al. 2012) and peat (Willemse et al. 2003) records throughout the  
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42 227 Kangerlussuaq region and in the widespread loess deposits in interior western Greenland.  
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44 228 These paleo-records suggest that aeolian activity has varied during the Holocene and that the  
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46 229 magnitude and frequency of aeolian processes is closely linked to both ice sheet hydrology  
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48 230 and proglacial geomorphology which control sediment supply and availability. The strong  
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50 231 katabatic winds also cause local erosion on exposed slopes (figures 3a) and these deflation  
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52 232 patches are widespread closer to the ice sheet, driven by strong winds ( $> 20 \text{ m S}^{-1}$ ) blowing  
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3 233 off the ice sheet. This erosion represents local re-working and translocation of soil and loess,  
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5 234 which has implications for local C and nutrient budgets.  
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7 235 **How are these linkages across the landscape changing? (figure 5)**  
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9 236 **Water** Although the vast majority of ice sheet melt is routed to the ocean, a substantial portion  
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11 237 is routed first across the terrestrial landscape, providing subsidies of water and sediment. For  
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13 238 Greenland as a whole, 69% of the runoff to the surrounding seas originated from the GrIS  
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15 239 and 31% came from outside the GrIS (from rain and melting glaciers and ice caps) (Mernild  
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17 240 and Liston 2012). For the GrIS specifically as a whole, about 75% of this proglacial  
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19 241 meltwater flows into rivers, and the remainder enters lakes at the margins of the ice (Lewis  
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21 242 and Smith 2009). These ice-marginal lakes may increase in number and/or size with  
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23 243 increased melt of the GrIS associated with a warming climate (figure 5). Proglacial lakes and  
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25 244 rivers fed by land-terminating glacial lobes receive large plumes of sediment-laden  
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27 245 meltwater. Sediment deposited by these rivers and lakes is the primary source of the fine  
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29 246 sediment transported in aeolian processes. An increase in the frequency of jökulhlaups, as  
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31 247 predicted by Russell et al. (2011), may consequently lead to an increase in sediment  
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33 248 deposition (figure 5), and therefore an increase in the magnitude and frequency of dust  
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35 249 storms, assuming sufficient aeolian transport capacity.  
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40 250 In periglacial areas removed from the direct influence of the ice sheet, the routing of  
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42 251 water across the landscape is impacted by seasonal and interannual changes in permafrost  
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44 252 dynamics, as well as by snow accumulation and melt, which are strongly influenced by  
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46 253 sublimation (Johansson et al. 2015). Global climate simulations suggest a widespread  
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48 254 increase in permafrost thaw in the 21<sup>st</sup> century, with increased movement of water through  
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50 255 the subsurface and, in some regions, increases in precipitation that outpace evaporation  
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52 256 increase (Lawrence and Slater 2005). These changes in water movement through the active  
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54 257 layer will affect weathering rates and the transport of solutes, including major cations, metals,  
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3 258 and trace elements (Jessen et al. 2014), and inorganic and organic carbon (Schuur et al.  
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5 259 2015). Thus, changes in permafrost cover and duration are likely to influence the hydrology  
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7 260 and biogeochemical dynamics of both terrestrial and aquatic ecosystems (figure 5). For  
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9 261 example, in Arctic Alaska, deepening of the active layer and melting of nutrient-rich  
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11 262 permafrost has enhanced the growth of herbaceous plants, which have encroached upon  
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13 263 shallow ponds and reduced open water cover by ~17% since 1948 (Andresen and Lougheed  
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15 264 2015). This unexpected dynamic further emphasizes the difficulty of predicting future  
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17 265 hydrologic mass balance on a landscape scale.

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21 266 Measurements and coupled hydrologic mass balance modeling in the Kangerlussuaq  
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23 267 area suggest that catchment water balance is spatially quite variable, in part as a result of the  
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25 268 steep precipitation gradient from the ice sheet westward towards the oceanic moisture source  
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27 269 (Johansson et al. 2015, Mernild et al. 2015). This variability has important implications in  
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29 270 terms of generalizing about terrestrial and aquatic ecosystem responses to climate change.  
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31 271 Water budgets of catchments and lakes isolated from direct impact of the GrIS will be  
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33 272 dependent on the balance between local precipitation and evaporation, including changes in  
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35 273 sublimation during winter and spring. In the Kangerlussuaq area, some lakes also exchange  
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37 274 water with a deep groundwater system through taliks (Johansson et al. 2015), which may  
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39 275 modulate the direct impacts of climate change. In the past, changes in regional temperature  
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41 276 and precipitation have produced considerable lake level changes. Geomorphic and  
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43 277 paleolimnological records in the Kangerlussuaq region document lake-level rises of 1.3 m  
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45 278 above modern during pluvial periods of the last 2000 yr and up to 18 m of lake level decline  
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47 279 during the mid-Holocene, when independent data suggest regional summer warming of 2-3°C  
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49 280 (McGowan et al. 2003, Aebly and Fritz 2009). Changes in climate seasonality are likely to  
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51 281 have prominent impacts on hydrologic mass balance.

52 282 **Carbon** Changes in climate have begun to alter the carbon (C) cycle linkages among glacial,  
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3 283 proglacial, aquatic and terrestrial systems throughout the Kangerlussuaq region in several  
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5 284 ways (figure 6). Increased spring warming and a longer melt season has expanded the melt  
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7 285 zone across the GrIS (Tedesco et al. 2012), increasing the region available for autotrophic  
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9 286 microbial communities in cryoconite and bare ice to colonize and grow. An earlier start to the  
10  
11 287 spring melt season will alter patterns of microbial cycling in supraglacial environments, and  
12  
13 288 potentially increase rates of net ecosystem production (NEP) and DOC export from the  
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15 289 glacier (figure 6a; Yallop et al. 2012; Lawson et al. 2014). Increased supraglacial ablation  
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17 290 rates will also increase the supply of sediment melting out from glacial ice (Stibal et al. 2008)  
18  
19 291 as there is strong evidence that much of the DOC exported from glaciers is derived from  
20  
21 292 microbial production in the supraglacial environment (Bhatia et al. 2013; Lawson et al.  
22  
23 293 2014). Increased microbial production associated with spring warming will therefore result  
24  
25 294 in greater DOC fluxes and earlier export of DOC and particulate organic carbon (POC) to the  
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27 295 subglacial environment and glacial outlet rivers (figure 6b; Lawson et al. 2014), as long as  
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29 296 increased glacial melt does not flush supraglacial microbes from the GrIS and offset DOC  
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31 297 production (Stibal et al. 2012). However, changes in DOC and POC export from the sub- and  
32  
33 298 supraglacial environments are unlikely to directly influence nearby lakes because of the  
34  
35 299 severe disconnect between glacial outwash and terrestrial systems. In fact, organic C  
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37 300 produced in supraglacial areas has little effect on aquatic and terrestrial ecosystems in the  
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39 301 Kangerlussuaq area until sediments are deposited on river banks where it is subsequently  
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41 302 carried across the landscape by aeolian transport (figure 6c). Estimates of organic C fluxes  
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43 303 from aeolian deposition ( $\sim 50 \text{ mg C m}^{-2} \text{ yr}^{-1}$ ) are about three orders of magnitude lower than  
44  
45 304 NEP in nearby proglacial lakes, and are therefore unlikely to significantly impact NEP in  
46  
47 305 these ecosystems. These aeolian carbon fluxes are, however, similar to rates of NEP on the  
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49 306 surface of glaciers in the area ( $5 \text{ to } 149 \text{ mg C m}^{-2} \text{ yr}^{-1}$ ; Stibal et al. 2012).  
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3 307 In a warming permafrost landscape, the composition of soil and lake DOC pools are  
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5 308 likely to change in response to shifts in terrestrially-derived C and internal lake dynamics.  
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7 309 DOC is a complex mix of compounds sourced from degraded terrestrial and aquatic primary  
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9 310 productivity and serves as a cross-ecosystem material that is dependent on direct and indirect  
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11 311 climatic influences. Decreasing DOC concentrations in the lakes over the past decade (Saros  
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13 312 et al. 2015) may result from multiple drivers including decreases in terrestrial subsidies  
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15 313 and/or increased sulfate deposition. Ultimately, the linkage between aquatic and terrestrial  
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17 314 systems will depend largely on landscape hydrological connectivity. Currently, there is a  
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19 315 strong link between aquatic and terrestrial DOC early in the growing season when spring  
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21 316 snowmelt runs off into lakes. However, this relationship weakens over the growing season as  
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23 317 soils dry and recharge from precipitation is low. Highly colored, diluted and possibly  
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25 318 photooxidized (Osburn et al. 2001) DOC was recovered from lakeshore wells in the  
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27 319 Kangerlussuaq region in early June; however, the same wells were dry and DOC content very  
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29 320 low in early August. Under scenarios of increased spring warming, we expect an  
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31 321 advancement in the timing and possibly the magnitude of this pulse of terrestrial DOC,  
32  
33 322 depending on how climate change affects surface and subsurface hydrology. In one scenario,  
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35 323 if rising temperatures lead to an increase in permafrost degradation throughout the growing  
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37 324 season, more DOC will be transported into surrounding lakes (figure 6d). Alternatively,  
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39 325 greater evapotranspiration may decouple permafrost meltwater from surrounding lakes,  
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41 326 resulting in a loss of watershed connectivity and limit total DOC transport (figure 6e).

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47 327 Shifts between allochthonous and autochthonous C sources in lakes will alter the  
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49 328 composition of the DOC pool, which may, in turn alter competitive interactions among  
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51 329 microbial species (Crump et al. 2003) and restructure community assemblages. In a highly  
52  
53 330 seasonal environment such as southwest Greenland (and the Arctic), changes to the temporal  
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55 331 inputs of soil DOC will likely lead to seasonal shifts in lake microbial communities toward  
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3 332 fast growing microorganisms that are able to rapidly utilize DOC inputs from soils. This  
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5 333 process may be amplified as ice-free durations of Arctic lakes have increased over the last  
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7 334 century (figure 6f) in response to climate warming (Magnusson et al. 2000). Extended ice-  
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10 335 free seasons have reduced under-ice mineralization and net C emissions in some regions  
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12 336 (figure 6g, h; Finlay et al. 2015) and increased C burial in lake sediments (figure 6i).

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14 337 Long-term changes in plant community composition driven by geomorphic processes  
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16 338 (Heindel et al. 2015), climate warming and/or large herbivores will also influence the link  
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18 339 between terrestrial and aquatic environments by altering terrestrial C pools. The low-shrub  
19  
20 340 tundra in the region has displayed divergent responses to warming when large herbivores  
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22 341 were excluded. For instance, warming without large herbivores reduced species diversity of  
23  
24 342 the plant community, while herbivory maintained this diversity even under warming (Post  
25  
26 343 2013). Moreover, when warmed and excluded from herbivory by caribou and muskoxen, the  
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28 344 tundra acted as a C sink ( $200 \text{ g C m}^{-2}$ ), but the area accumulated less than half that amount  
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30 345 when exposed to herbivores (Cahoon et al. 2012). However, when exposed to herbivores,  
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32 346 graminoids continued to dominate and the communities accumulated less than half the  
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34 347 amount of C relative to exclosed sites (Cahoon et al. 2012), providing evidence of a strong  
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36 348 trophic interaction that can limit terrestrial C uptake (figure 6j). With greater leaf area, shrubs  
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38 349 tend to fix more C than herbaceous species (Cahoon et al. 2012), while shading from a closed  
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40 350 canopy can keep soils cool and limit respiratory losses. Although shrub tundra acts as a  
41  
42 351 stronger C sink, woody stems provide a more recalcitrant source of C than herbaceous  
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44 352 communities (Hobbie 1996); therefore, greater C uptake associated with shrub expansion  
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46 353 may not necessarily lead to greater DOC available for transport to aquatic environments, at  
47  
48 354 least in the short-term. Nevertheless, changes in the relative abundance of deciduous shrubs  
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50 355 will influence the quality and quantity terrestrial C pools that serve as an upstream source of  
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52 356 DOC for aquatic environments.  
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3 357 Changes in plant community composition in response to warming will directly alter  
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5 358 the terrestrial C cycle, but also affect the fraction of belowground DOC available for  
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7 359 transport. Whether the link between terrestrial and aquatic environments will strengthen or  
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9  
10 360 weaken in response to warming will depend on the synergy of watershed connectivity and the  
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12 361 relative fraction of labile DOC. Changes in terrestrial DOC production and meltwater  
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14 362 delivery of terrestrial C (either from permafrost or snowmelt) are crucial interacting factors  
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16 363 that warrant further investigation in southwest Greenland and throughout the Arctic.  
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18 364 **Nutrients and other elements** The hydrological disconnect between the glacial outwash plains  
19  
20 365 and much of the terrestrial landscape is a key constraint on nutrient cycling within the  
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22 366 Kangerlussuaq region (figure 7). This separation creates a prominent role for aeolian and  
23  
24 367 atmospheric transport pathways between the ice sheet and adjacent land surface with  
25  
26 368 important consequences for nutrient stoichiometry. Nitrogen is typically transported in  
27  
28 369 dissolved forms, whereas P adsorbs to sediments and particles, and so waterborne P transport  
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30 370 is generally efficient within energetic sediment-laden riverine environments (e.g., the fluvial  
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32 371 outwash plain), but more limited where stream flows are slow or dominated by seepage (e.g.,  
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34 372 on the terrestrial land surfaces around Kangerlussuaq where the low precipitation:evaporation  
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36 373 ratio limits development of streams and rivers). On the ice sheet surface, microbial nutrient  
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38 374 processing hotspots include “dirty ice” (Yallop et al. 2012) and cryoconite holes (Stibal et al.  
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40 375 2012; Telling et al. 2012). Clean ice has inorganic N:P ratios of 86:1, indicating that N is  
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42 376 sourced via wet deposition (Hastings et al. 2009). Therefore, dust (estimated N:P ratio of 2:1)  
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44 377 is probably important as a P fertilizer to facilitate microbial growth (Mindl et al. 2007).  
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46 378 Where algae grow directly on the ice surface, inorganic N:P ratios are lower (41:1), probably  
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48 379 indicating patches where P fertilization through dust accumulation has modified the local  
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50 380 environment (Stibal et al. 2010) and N has been sequestered by algae (Yallop et al. 2012).  
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52 381 The highly variable N:P ratios in cryoconite holes (10–91:1), where N<sub>2</sub>-fixing cyanobacteria  
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3 382 are common, indicate strong and divergent biological modification of inorganic nutrients  
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5 383 within these environments (Telling et al. 2012). Areas of dust accumulation may therefore  
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7 384 stimulate localised 'patchy' development of algae on ice with significant increases in  
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9 385 pigmented biomass (Yallop et al. 2012; Lutz et al. 2014).

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11 386       Glacial runoff waters have much lower N:P ratios (dissolved 10:1; total 2:1) than on  
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13 387 the ice surface, suggesting biogeochemical modification on the passage through the  
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15 388 subglacial system (Yde et al. 2010), where microbial processing and the addition of glacial  
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17 389 flour increase the bioavailable P (Stibal et al. 2012; Wadham et al. 2013). Discharge into  
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19 390 proglacial lakes enhances N:P ratios (to 14–24:1) because they often have abundant  
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21 391 cyanobacterial N<sub>2</sub> fixing communities and probably remove P from the water through rapid  
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23 392 sedimentation of organic- and inorganically-bound particulates (McGowan et al. 2008). In  
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25 393 contrast, the sediment-laden river waters (2–15 kg m<sup>-3</sup> (Cowton et al. 2012) efficiently  
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27 394 transport particulate-bound P and dissolved N to the sandurs, fjord and coastal regions  
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29 395 (Hawkings et al. 2015). Nutrient ratios within the river- fjord system are most likely modified  
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31 396 primarily through physical and chemical processes because the turbulent conditions are  
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33 397 inhospitable for the development of many biota. Apart from some N uptake and  
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35 398 sedimentation by primary producers within the fjord ecosystem (NO<sub>3</sub>-N concentrations are  
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37 399 116 µg L<sup>-1</sup>; Hawes et al. 2012), N is probably exported in dissolved form to the coastal  
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39 400 regions (Hawkings et al. 2015), with implications for sustaining productivity of plankton and  
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41 401 ice algae in coastal waters.

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43 402       Inorganic N:P ratios within snowfall (15–278:1) indicate significant N delivery as wet  
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45 403 deposition (0.8 kg N ha<sup>-1</sup> y<sup>-1</sup>; C. Curtis, pers. Comm.), whereas snow with particulates has a  
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47 404 lower ratio (11:1) indicating enrichment with P, most likely from dust. Therefore direct wet  
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49 405 and dry deposition are major determinants of terrestrial nutrient availability, and nutrients are  
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51 406 most mobile during spring snowmelt when ephemeral rivers activate (Johansson et al. 2015).

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3 407 Soil N:P ratios of 2–13:1 around Kangerlussuaq (c.f. mean global ratios 13:1) suggest relative  
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5 408 P enrichment, consistent with observations that soil surface layers at Kangerlussuaq are  
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7 409 influenced by aeolian silt deposition (Nielsen 2010), and that P availability is generally  
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9 410 greater in geologically young soils. The variable soil N:P ratios in Kangerlussuaq also  
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11 411 suggest heterogeneity of nutrient delivery and processing, as demonstrated by the mosaic of  
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13 412 vegetation types which are also strongly constrained by water availability (Thing 1984).  
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15 413 Herbivore grazing can modify nutrient cycling locally, e.g. reindeer use urine and feces to  
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17 414 fertilize local areas and encourage *Poa pratensis* growth (Thing 1984). Due to snowmelt  
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19 415 percolation, subsurface soil waters are enriched in nitrogen during the spring, mostly as  
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21 416 organically bound forms (N:P ratio of 25:1) but the ratio reaches 7:1 by late summer when N  
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23 417 availability declines.

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27 418 Lake measurements show a spring snowmelt N pulse, delivered predominantly as  
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29 419 ammonium but with some nitrate (Whiteford et al. 2016). Lake bioavailable N becomes  
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31 420 depleted throughout the growth season. Importantly, the extremely high N:P ratios within  
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33 421 lake seston and organically bound fraction (122–305:1) indicate both P removal through  
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35 422 sequestration into lake sediments (N:P ratio 6:1) and the retention and accumulation of N in  
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37 423 lakes, most probably incorporated into recalcitrant dissolved organic material which  
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39 424 accumulates slowly in the closed lake basins (Anderson and Stedmon 2007). This long-term  
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41 425 N retention in lake waters probably explains why a period of pelagic P limitation occurs in  
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43 426 the spring under ice (Whiteford et al. 2016) when algal growth begins, but lakes are sealed  
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45 427 from atmospheric P (dust) sources. Because of limited surface outflow from these lakes, the  
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47 428 primary nutrient transfer pathways between lakes and the terrestrial areas are probably  
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49 429 subsurface flows (Johansson et al. 2015) and transfer by biota. For example, chironomids can  
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51 430 fertilize soils adjacent to lakes when they emerge as adults (an estimated potential local load  
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53 431 of 0.5 kg N ha<sup>-1</sup> yr<sup>-1</sup> N and 0.05 kg P ha<sup>-1</sup> yr<sup>-1</sup> N), and water birds such as geese and ducks  
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3 432 may be significant vectors. Canada Geese commonly nest and forage along lake shores  
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5 433 considerably more than White-fronted Geese, with consequences for nutrient cycling and  
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7 434 above-ground primary production as well as species composition of vegetation. Later, during  
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9 435 moult, both species of geese specialize on repeated grazing of grasslands and open moss mats  
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11 436 within 40 m of the water's edge, habitually returning to the water to rest and preen in safety  
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13 437 from terrestrial predators. Fecal deposition of material obtained from foraging in terrestrial  
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15 438 habitats in the vicinity of lakes is thus deposited in or near the water in the form of organic  
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17 439 material and the products of protein metabolism, which includes soluble nitrogen compounds.  
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19 440 Hence, the general increase in moulting goose numbers (regardless of species composition) in  
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21 441 the vicinity of lakes in this area over the last three decades in summer has likely had a major  
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23 442 effect on vegetation communities and their carbon and nitrogen dynamics. Because the  
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25 443 density of lakes is high in this region (>20,000 lakes), and there is a significant discrepancy  
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27 444 between N:P ratios in lake and terrestrial organic matter, there is great potential for trophic  
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29 445 interactions between lake and land to modify nutrient ratios.

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34 446 **Broader anthropogenic influences** Interactions between climate, dust production, atmospheric  
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36 447 pollutants and trophic dynamics have the potential to significantly modify a number of  
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38 448 regional biogeochemical linkages in the future. Increasing GrIS surface melt and subsequent  
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40 449 Watson River runoff in the future (Mernild et al. 2011) will increase nutrient export from the  
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42 450 inland ice to the fjord and coast and expand deposition of dust within the sandur (Yde et al.  
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44 451 2014). Future nitrogen deposition will depend on global economic development and  
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46 452 legislation, but is likely to increase, with implications for all elements of the Kangerlussuaq  
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48 453 system. Together, these changes will probably alter the N:P delivery to terrestrial and ice  
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50 454 sheet areas. Plant phenological advance has influenced trophic interactions between  
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52 455 producers and consumers, possibly contributing to a decline in calf production in the local  
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54 456 caribou population (Kerby and Post 2013). The effect of hunting pressures also needs to be  
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3 457 considered. Heavy metal contaminants such as lead and mercury have been recorded in  
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5 458 western Greenland since AD 1800 and AD1900, respectively (Bindler et al. 2001, Lindeberg  
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7 459 et al. 2006). A particular consideration is the special meteorological conditions in  
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9 460 Kangerlussuaq that appear to have concentrated mercury (3-5 fold increases in concentrations  
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11 461 and accumulation rates over the last century), but the effects on biota are so far not  
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13 462 extensively studied. Little is known of how delivery of other micro-nutrient elements (e.g.,  
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15 463 Zn, Cu, Mn, Mg, Co, Bo) may change in the future, with implications for microbial growth  
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17 464 on the ice sheet and lakes. Lake water sulfate concentrations have increased across the  
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19 465 Kangerlussuaq region over the past decade (Saros et al. 2015), raising intriguing questions  
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21 466 about the potential for a marine-terrestrial-freshwater linkage. Oceanic phytoplankton  
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23 467 produce dimethyl sulfate (DMS), which is aerosolized, transformed into methanesulfonic acid  
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25 468 (MSA), and transported onto landmasses. Sharma et al. (2012) noted significant increases in  
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27 469 MSA over the past decade in the Arctic, indicating a possible role for biogenic sulfate  
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29 470 delivery and deposition across the study area. Together, these examples indicate how global  
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31 471 change processes can initiate localized influence on the biogeochemistry of the  
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33 472 Kangerlussuaq region.

### 38 473 **Conclusion**

39 474 The Kangerlussuaq area of southwest Greenland is changing rapidly: regional warming is  
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41 475 driving increased seasonal melt on the ice sheet, altering phenology, and changing landscape  
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43 476 hydrology with associated effects on lakes and ponds. Some of these changes are interacting  
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45 477 in unpredictable ways (meltwater pulses and dust production) while others may have  
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47 478 cascading effects, such as altered herbivore densities on tundra vegetation and soil C  
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49 479 dynamics. Superimposed on these climate driven processes are chronic, subtle changes in  
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51 480 atmospheric pollutants, which may have synergistic effects, for example, altered N-loading  
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53 481 on soil nutrient pools and hence soil microbiology. The cross-system linkages between  
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3 482 geomorphic processes and ecosystems that influence regional biogeochemical cycling may  
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5 483 change in unpredictable ways because of the broader regional climate changes that go beyond  
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7 484 temperature: e.g., altered seasonality of precipitation, wind speeds and evapotranspiration.  
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9 485 The effects of these complex linkages for regional carbon dynamics and sequestration  
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11 486 highlight the need to take a holistic view of the changing climate, geomorphic and ecological  
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13 487 systems as they influence both aquatic and terrestrial communities in the 21<sup>st</sup> century as the  
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15 488 Arctic continues to change.  
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3 762 **Figure legends**  
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6 764 **Figure 1.** The area around Kangerlussuaq airport showing the high density of lakes and their  
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8 765 juxtaposition to the Greenland ice sheet, its outlet glaciers and the outwash plains.

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11 767 **Figure 2.** Key components of the Kangerlussuaq ecosystems. (a) Dwarf shrub tundra  
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13 768 (Photograph: John Anderson). (b) Steppe adjacent to the GrIS (Photograph: John Anderson).  
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15 769 (c) Rapid ecotonal transitions adjacent to the Isunguata Sermia glacier (see Figure 1)  
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17 770 (Photograph: John Anderson). (d) An ice dammed lake adjacent to the Russell Glacier (see  
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19 771 Figure 1) with dry, shallow ponds in the foreground; note the fossil shore-line associated with  
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21 772 a previous high stand of this lake (Photograph: Ladislav Hamerlik). The two large herbivores  
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23 773 found in the Kangerlussuaq area of SW Greenland: (e) Adult male caribou, (Photograph:  
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25 774 Eric Post). (f) Two adult male Musk ox (Photograph: Eric Post).

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29 776 **Figure 3.** Aspects of aeolian activity around Kangerlussuaq. (a) Wind scouring of the steppe  
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31 777 landscape adjacent to the GrIS margin (Photograph: John Anderson). (b) A late winter dust  
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33 778 storm blowing along Sandflugtdalen (Photograph: John Anderson). (c) The sandur  
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35 779 immediately below the terminus of the Isunguata Sermia glacier (see Figure 1) (Photograph:  
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37 780 John Anderson). (d) Aeolian silt deposited in a lake watershed at an altitude of >500 m some  
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39 781 6 km south of the Ørkendalen sandur; the dust was originally deposited on snow in late  
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41 782 winter (Photograph: John Anderson).

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45 784 **Figure 4.** Polar views of recent (a) temperature and (b) precipitation anomalies for the period  
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47 785 2001–2014 compared to 1979–2000 showing the recent climate change in west Greenland,  
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49 786 particularly the marked warming. Maps generated via ClimateReanalyzer.org (Climate  
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51 787 Change Institute, University of Maine).



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5 789 **Figure 5.** A schematic representation of the possible changes in key landscape features,  
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7 790 geomorphic and ecosystem processes in the paraglacial of the Kangerlussuaq area between  
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9 791 the present day (upper panel) and 2100 AD (lower panel). Key geomorphic/landscape  
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11 792 features include the sandurs (glacio-fluvial outwash plains [GFP]), dunes, blow-outs,  
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13 793 moraines, ice-marginal lakes. Note the substantial retreat of the outlet glacier, the  
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15 794 development of ice-dammed lakes, increased biological activity on the glacier/GrIS (with  
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17 795 GFG fluxes) and hydrological loss; dune expansion and transfer of aeolian material from the  
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19 796 sandurs to adjacent terrestrial and limnic ecosystems. On land, deepening active layer depth  
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21 797 may increase surface water accumulation, with associated GHG fluxes, expansion of shrub  
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23 798 tundra and re-vegetation of blow-outs. Lakes will be ice-free for longer with altered gas  
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25 799 exchange.

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32 801 **Figure 6.** A conceptual diagram showing the C cycle processes and interconnectedness  
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34 802 between glacial, terrestrial and aquatic ecosystems in the Kangerlussuaq region today and in  
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36 803 the future. Under a warming climate (dashed lines), supraglacial NEE is expected to reach  
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38 804 peak flux earlier in the growing season (a), driven by earlier and greater input from alluvial  
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40 805 deposits as the glaciers retreat (b). This may result in greater DOC export to proglacial lakes  
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42 806 through the active layer (c). Warming may lead to greater lake terrestrial NEE, depending on  
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44 807 the depth of permafrost thaw (d), shrub expansion dynamics (e) and the presence of  
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46 808 herbivores (f; plot adapted from Cahoon et al. 2012). Changes in permafrost and terrestrial  
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48 809 NEE will like affect the timing and magnitude of DOC input to lakes, depending on whether  
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50 810 permafrost meltwater acts as a vector and is transported to lakes (g, h). Similar to pan-Arctic  
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52 811 observations, we expect warming to extend the ice-free period of lakes (i) and lead to earlier  
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54 812 peak CO<sub>2</sub> flux in spring and later CO<sub>2</sub> flux in fall (j). A similar pattern in primary



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3 813 productivity (k) and sedimentation rates (l) is likely to occur under warming in response to an  
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5 814 extended growing season.

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10 816 **Figure 7.** A conceptual diagram of the atomic N:P ratios and cross system transfers of  
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12 817 nitrogen (black arrows) and phosphorus (white arrows) among components of the  
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14 818 Kangerlussuaq landscape. The thickness of the arrows indicates the degree of influence that  
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16 819 the transfer has on N:P ratios of the receiving system (no/ negligible influence = no arrow,  
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18 820 and categories indicate small, medium and large influence). N:P ratios are measured on the  
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20 821 dissolved inorganic (generally bioavailable) fraction, unless indicated with an asterisk\* where  
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22 822 total digested nutrient concentrations were measured. Values in standard text are data derived  
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24 823 directly from Kangerlussuaq, whereas those in italics derive from published arctic or  
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26 824 subarctic values.

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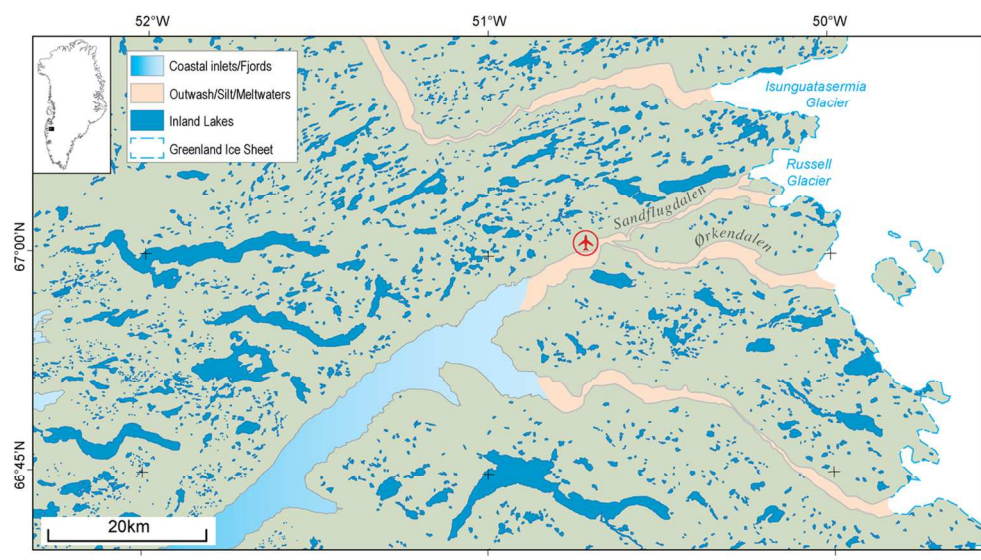
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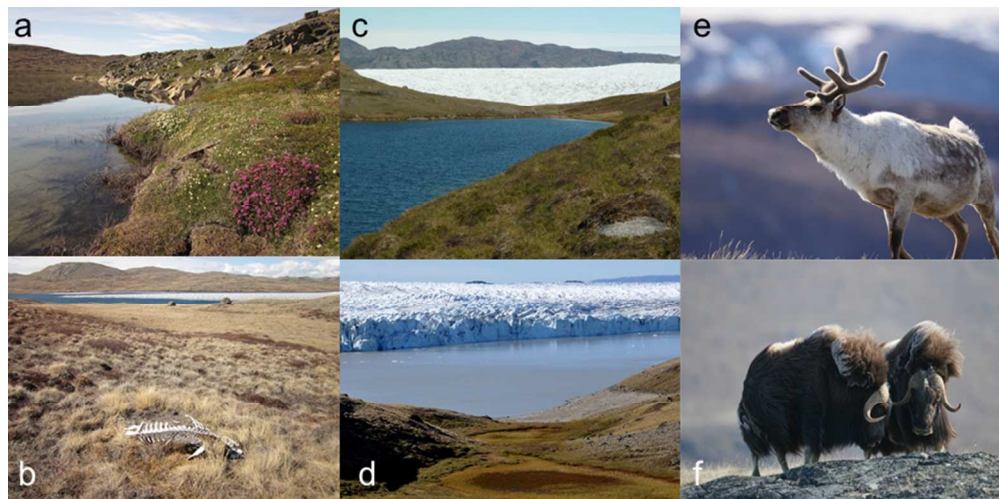
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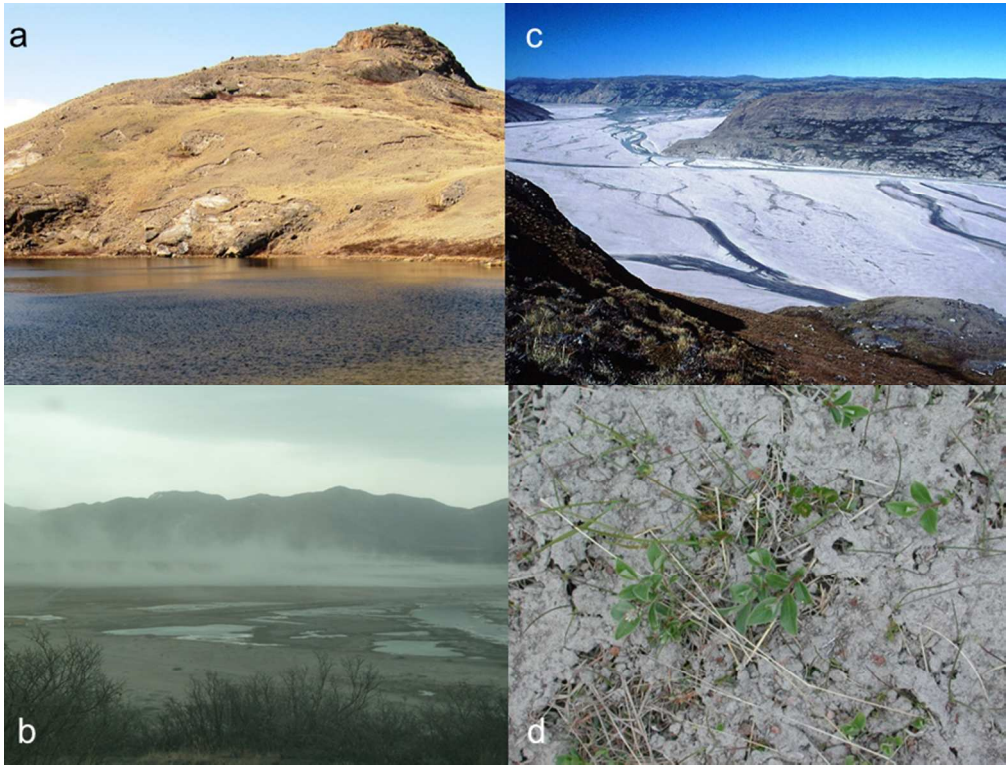


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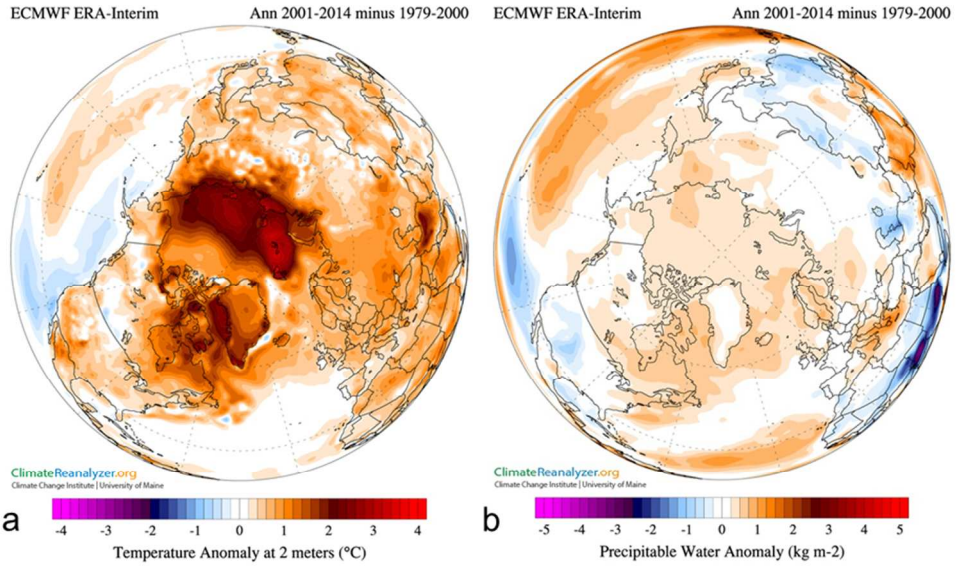
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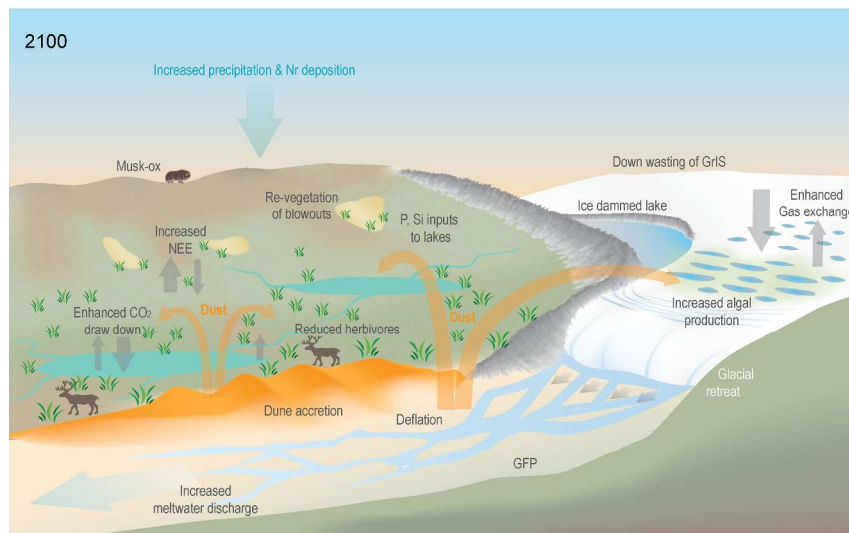
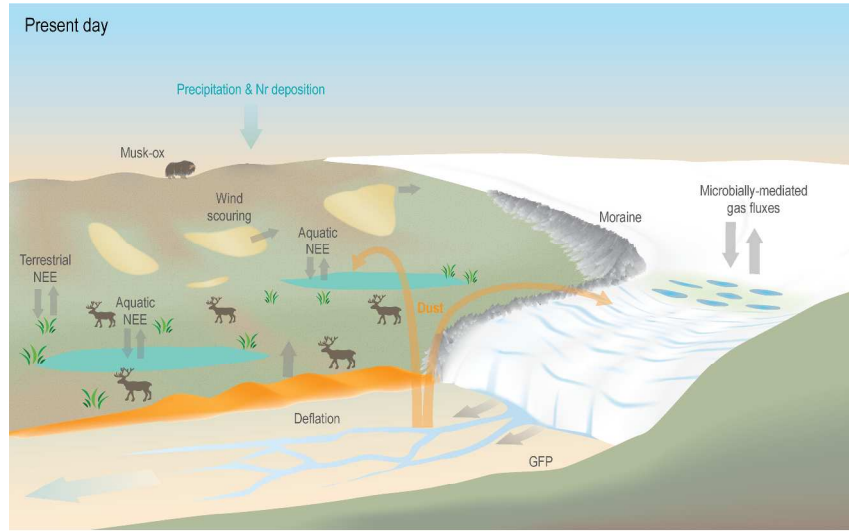


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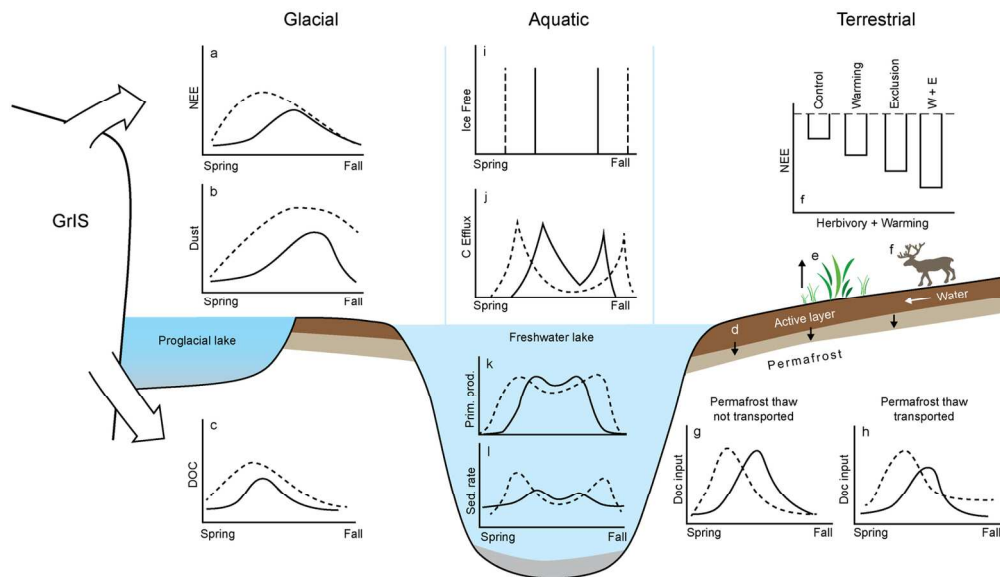
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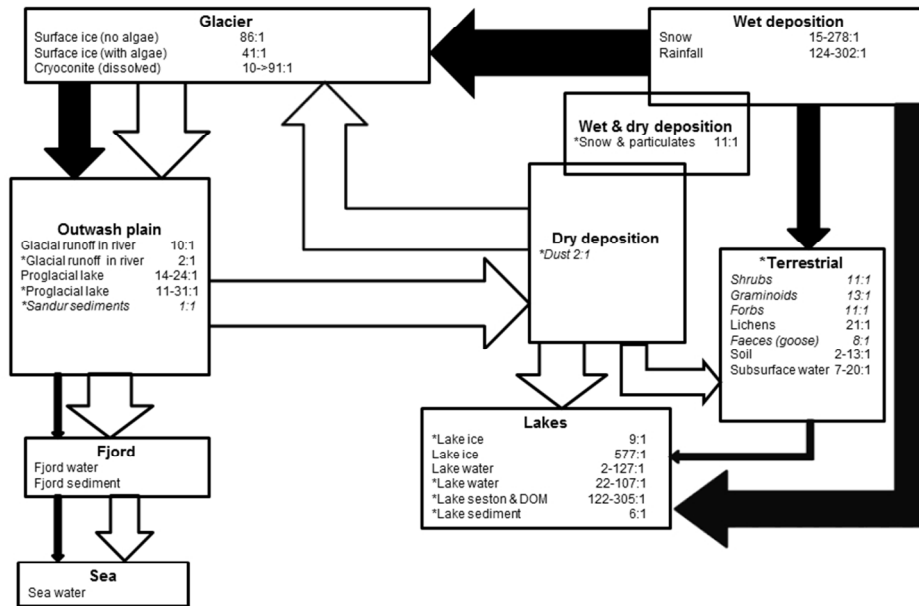




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254x190mm (96 x 96 DPI)