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We cannot shrug off the shoulder seasons: addressing knowledge and data gaps in an Arctic headwater

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Abstract

As environmental change in the Arctic accelerates, there is a growing need to accurately quantify the response of Arctic ecosystems throughout the year. To assess the temporal coverage of observations of carbon and nutrient fluxes, we used literature synthesis, quantitative meta-analysis, and exploration of a novel biogeochemical dataset from one of the best-documented Arctic ecosystems: the headwaters of the Kuparuk River in Northern Alaska. The meta-analysis of 204 peer-reviewed studies revealed a strong temporal gap in observations of biogeochemistry and hydrology of the Kuparuk River, with substantially fewer observations from the early and late 'shoulders' of the thaw season (defined as the period before snowmelt or after plant senescence). To test and illustrate how much this bias might influence fundamental ecosystem level measurements, such as riverine carbon and nutrient fluxes, we used high-frequency, in-situ water chemistry sensors to estimate riverine export budgets across the thaw season for dissolved organic carbon (DOC) and nitrate (NO\textsubscript{3}\textsuperscript{-}) in the Kuparuk headwaters. With this novel dataset, we found that a large proportion (~30%) of the annual export of DOC and NO\textsubscript{3}\textsuperscript{-} occurred during the shoulder seasons, which are not well characterized even for this well-documented Arctic system. These analyses raise the broader question: what ecological information are we missing by giving these seasons the 'cold shoulder'? As climate change alters seasonality, filling this major data gap in the shoulder seasons is crucial to understand the response of Arctic ecosystems.

1. Introduction

Carbon and nutrient budgets are fundamental to basic ecosystem processes [1, 2]. In recent years, focus has turned towards understanding high-latitude terrestrial and aquatic contributions to global change budgets and feedbacks, which is a challenging objective in these remote regions. Arctic ecosystems contain a globally-relevant amount of organic material [3] held in permafrost soils [4–6] and stored in above- and below-ground plant biomass [7, 8]. These abundant sources of organic matter are susceptible to mobilization as dissolved organic matter (DOM) from land to water [9–15]. While liquid water flow in Arctic headwater networks is often constrained to a short flow season [16], the carbon and nutrients released into and subsequently exported to Arctic rivers contribute to global carbon budgets [17–19]. Accurate biogeochemical budgets across the whole season are critical reference points for earth system models and are required to predict the strength and timing of climate feedback mechanisms in the Arctic [7, 20, 21]. Consequently, there is a growing need to identify data and knowledge gaps that may limit quantification of Arctic ecosystem budgets.

The Arctic is experiencing profound and widespread modification of the ecosystem processes regulating river exports [22–24]. First, the speed and seasonality of warming is increasing, amplifying warming affects that are felt in the Arctic and beyond [25]. With Arctic warming comes dramatic changes to plant phenology and growth [26, 27],...
which alter terrestrial and aquatic vegetation communities [28, 29]. In combination with terrestrial ecosystem changes, hydrologic intensification is resulting from interactions among a broadened season [16, 30–35], increased frequency and magnitude of precipitation events [36–40], and accelerating permafrost thaw [13, 24, 41–43]. As the impacts of climate change progress, hydrologic intensification will likely affect the timing and intensity of high-flow events in high-latitude regions [39, 40], control the delivery of organic and inorganic materials to Arctic surface waters [32, 44–46], alter local nutrient availability for aquatic food webs [28, 47, 48], and impact downstream carbon and nutrient exports across the flow season [49–54]. These documented changes are also part of a positive feedback accelerating material release, where warming climate, increasing active layer depth, and changing disturbance regimes can trigger rapid permafrost thaw via thermokarst features [13, 15, 21, 43, 53, 55–58]. Terrestrially-derived carbon and nutrients are then released into and subsequently exported through Arctic rivers that contribute to global carbon budgets [17–19, 47, 59]. Taken together, these factors could trigger important shifts in riverine biogeochemical fluxes, with unknown ecological impacts.

Because river exports are both sensitive to and indicative of broad ecosystem change [60–62], accurately quantifying watershed exports could provide an early warning of ecosystem shifts in remote areas. Therefore, the principal motivation of our study was to assess the current state of knowledge for carbon and nitrogen export in an Arctic headwater network, with emphasis on capturing dynamics across the entire flow season in changing Arctic ecosystems. We first present a meta-analysis where we quantify temporal data coverage of the ‘shoulder’ seasons and storm events for the Kuparuk River in northern Alaska (table 1), one of the most studied rivers and watersheds in the Arctic as it is associated with the US Arctic Long-Term Ecological Research (LTER) site that has been conducting extensive ecological monitored since the late 1970 s (figure 1). For the purposes of this study, we define the Arctic river shoulder seasons as the period from the onset of flow in the headwaters to the end of the snowmelt, and the transitional period from the senescence of deciduous plants until the headwaters refreeze and cease to flow [47, 63]. By this definition, the Kuparuk headwater shoulder seasons are typically early to late May and September. We recognize that the definition of ‘shoulder season’ is innately place-dependent and must be defined empirically for each specific study location [64]. Second, to quantify the potential importance of shoulder season data gaps, we present a novel, high-frequency dataset of carbon and nitrogen flux in the Kuparuk River headwaters. Specifically, we analyzed this dataset to identify the timing and magnitude of major biogeochemical fluxes across a greater portion of the shoulder seasons as well as individual storm events. Third, we propose several key considerations to improve current and future estimates of Arctic ecosystem budgets that incorporate the reality of changing hydrology and shifting seasonality across permafrost-zone watersheds. Finally, we discuss other knowledge gaps from different ecosystem components that are connected to riverine biogeochemistry.

We emphasize that the driving purpose of these efforts was to bring multiple lines of evidence together from a well-documented Arctic watershed to demonstrate that as a scientific community, we should give greater attention to when observations are made in high-latitude ecosystems. We conclude that filling shoulder season data gaps offers opportunities to better understand changing seasonality in hydrological and ecological conditions of Arctic ecosystems.

1.1. What we know: seasonality of biogeochemical budgets in the Kuparuk headwaters

To place the shoulder seasons of high-latitude river networks in broader context, we briefly review the current state of knowledge throughout the year for the Kuparuk River headwaters (figure 2(A)). Current conceptual understanding of the Kuparuk headwaters suggests that the majority of annual biogeochemical exports occur during the snowmelt period (freshet); then, the mid-flow season is responsible for the majority of terrestrial and instream biogeochemical processing, as in figures 2(B) and (C) [12, 65]. Our current conceptualization for riverine export is based largely on monitoring and load modeling using paired water chemistry and discharge taken at relatively low sampling frequency. This understanding is held for many Arctic watersheds [66], but should not be extended to all as most watersheds are still undocumented and may span a much greater diversity of physical and ecological drivers and biogeochemical characteristics than what is known for the Kuparuk headwaters [67]. Hence, the details of the Kuparuk ecosystem and biogeochemical dynamics below may not apply to all Arctic headwaters.

In the Kuparuk, as snow melts in the spring, frozen ground limits soil water storage and enhances water runoff to the river network (figure 2(B)). With the snowmelt comes large pulses of water that is rich in dissolved and particulate organic matter (DOM and POM, respectively) and associated nutrients, which are in turn exported downstream [49], resulting in increased aquatic productivity [28] (figures 2(C), (F)). The relatively short snowmelt occurs over several days to weeks and represents ~35% of export in the Kuparuk River [68]. The significance of the spring snowmelt period has been shown in other Arctic rivers, representing between 20%–70% of annual carbon exports [50, 69, 70]. The spring snowmelt typically generates highly bioavailable DOM in the river network, which reflects the recent origin of the DOM from fresh litter and surficial soil horizons leaching
with little previous decomposition [65] or photo-processing on the landscape or in the river [71–73]. Simultaneously, frozen soil restricts the flow of water to organic horizons during snowmelt, introducing dissolved organic nitrogen (DON) into adjacent river networks [74–76]. A portion of the DON may remain on site or be transformed into inorganic forms that can increase nutrient availability for terrestrial plants and soil microorganisms while some of the DON is exported downstream before mineralization to dissolved inorganic nitrogen (DIN) [77] (figure 2(C)).

As thaw progresses in the Kuparuk, biological activity and deepening water flow paths increasingly control the amount of DOM and nitrogen as DON or DIN reaching the river network and leaving it via downstream export [46] (figure 2(C)). The seasonal thickening of the active layer facilitates the movement of water through deeper mineral soil profiles where it interacts with solute-rich permafrost [16, 74, 78] (figure 2(E)). These deeper flowpaths either promote DOM leaching from detritus and above-ground plant biomass as water builds up at the soil-permafrost interface, or increase rates of decomposition and increase sorption to mineral particles [24, 79]. Newly released DOM and DIN are then exported laterally by surface or subsurface flow paths [53], potentially decreasing soil nutrient availability and altering the chemical composition of waters draining permafrost landscapes [65, 74] (figure 2(C)). As inorganic nitrogen (N) and phosphorus (P) become increasingly limiting as a result of biotic demand, mobilized DOM continues to fuel instream respiration [29, 80, 81]. While low temperatures experienced in the early flow season may limit carbon processing by bacterial respiration, once DOM enters into the stream channel and is moved along the aquatic continuum, it can still experience high rates of processing via photo-mineralization and some partial photo-oxidation as it is transported downstream [71, 72] (figure 2(D)). Photo-oxidation requires sunlight to reach the water column, so its influence on DOM peaks in June and decreases later in the flow season, while hillslope
Figure 2. We present a timeline of a typical field season from the ‘early’ to the ‘late shoulder season in the Kuparuk headwaters (row A). Along this generalized timeline, we indicate key seasonal benchmarks light grey boxes. The directions of major changes are noted in the text by arrows (▲ for increasing, ▼ for decreasing). In the following panels (rows B–G), we present current and projected patterns for several important abiotic and biotic parameters: (B) river discharge (blue lines); (C) dissolved organic matter (DOM, brown line) and dissolved inorganic nitrogen (yellow line, DIN) as flux, (D) solar UV and surface temperature (black and dark grey lines, respectively); (E) thaw depth extent (light grey lines); (F) terrestrial and aquatic productivity (dark green and light green lines); and (G) microbial activity (red lines). In rows (B)–(G), current or unchanging patterns are signified by a solid line, while expected changes for each parameter are signified by dashed lines. We use long dashes to indicate low uncertainty in the magnitude, direction, and pattern of projected changes and short dashes to signify high uncertainty. The background color gradient represents the temporal uncertainty in seasonal changes to each parameter. Dark grey denotes a lack of study and/or an existing data gap, while the white background indicates a higher degree of temporal understanding of the projected changes.

connectivity is still increasing via active layer thickening until late flow season [79] (figure 2(E)). Concurrently, in the late flow season, DON may be sorbed to sediment particles or mineralized to DIN, resulting in increasing lateral flux of inorganic forms of nitrogen, such as NO$_3^-$ [16, 75, 77]. While late-season DOM often exhibits low bioavailability [82], the decline of photo-processing and influx in DIN may result in a
brief increase of late-season heterotrophic response [77] (figure 2(G)).

1.2. What we need to know: identifying Arctic data and knowledge gaps
The pioneering ecological observations and discoveries briefly reviewed above have provided valuable insight into hydrochemical dynamics in high-latitude watersheds. However, the combination of inconsistent sampling regimes, a lack of coverage across the entire flow season, plus genuine safety, logistic, and financial constraints create significant challenges for estimating biogeochemical budgets and capturing hydrologic behavior in remote Arctic regions [22, 83, 84]. As a result, our fundamental understanding of carbon and nitrogen budgets is likely based on an incomplete characterization of a generalized Arctic flow season (e.g. figure 2(A)). Leveraging the rich ecological documentation from the Arctic LTERR, we assessed the historical temporal coverage of ecological studies from the Kuparuk. We analyzed temporal coverage of studies from different ecological disciplines to identify where relevant understanding may be lacking. Specifically, we used a literature meta-analysis of 204 studies performed on the Kuparuk River (figure 1) (detailed meta-analysis methods can be found in supplement) (available online at stacks.iop.org/ERL/15/104027/mmedia).

Our literature analyses uncovered quantifiable temporal biases in these research studies and showed that these biases were topic specific. Generally, across all Kuparuk headwater environmental studies, the months of June, July, and early August are the most intensively studied. Average study start and end dates were May 25 and August 27, respectively, though study temporal extent varied considerably by study topic, with thermal or active layer thickness (ALT) studies having the most complete coverage (figure 3(A)). Relative to the overall mean, studies specifically associated with hydrology and biogeochemistry had somewhat narrower temporal extent but longer study duration. Average start dates for hydrology and biogeochemical studies occurred in late-May, likely the result of efforts to account for the snowmelt period, and end dates fell in mid to late August (figure 3(A)). The density distributions of study extent further revealed that among all study topics, the shoulder seasons are less intensively studied than the ‘peak’ study months (figure 3(B)). More specifically, hydrologic studies were most dense during the snowmelt period of late May to early June, with fewer studies in late August and September. Biogeochemical studies made up the greatest proportion of all published literature on the Kuparuk River (~38%) and showed that watershed biogeochemistry was most extensively studied in late June through early August, with fewer studies in May and September.

While the differences in density distributions of studies may be the result of logistical challenges or the direction of specific scientific interest during certain study periods, the paucity of studies during both early and late shoulder seasons demonstrates a critical data and therefore potential knowledge gap in our understanding of this Arctic watershed, despite it being one of the most extensively studied in the Arctic. Though our analysis characterizes one river that may not represent all Arctic study sites, these temporal data gaps very likely exist for less well-documented Arctic rivers [67]. Recognizing and striving to address these temporal data gaps in our future monitoring regimes and study designs presents exciting opportunities for many ecological disciplines to expand our understanding of seasonality and biogeochemistry in northern high-latitude rivers.

1.3. Striving to fill the data and knowledge gaps: a case study the Kuparuk headwater carbon and nutrient budgets
It is well established that permafrost watersheds are undergoing major ecological changes with riverine carbon and nutrient exports increasing in nearly all monitored watersheds [24, 62]. Therefore we focus on a riverine carbon and nutrient budgets in the Kuparuk headwaters as a case study evaluating the quantitative importance of the shoulder season data gap. Improved quantification of carbon and nutrient exports is key because these exports remain a large sources of uncertainty in predicting global ecosystem carbon balance [7, 21, 57, 85]. However, accurate riverine budgets rely on measurements of both concentration and discharge, making them sensitive to uncertainty in either parameter [86–88]. First, as illustrated by the meta-analysis approach, ecosystem budgets are often estimated using concentrations and discharge data collected from irregular opportunistic or low-frequency periodic (i.e. weekly or monthly) sampling regimes with limited thaw season coverage. Both sampling approaches typically results in uncertainty and underestimates of riverine budgets [89]. To assess the seriousness of this gap, we collected measurements of river biogeochemistry and hydrology in the Kuparuk further into the shoulder seasons (table 1). Second, these sampling approaches also lead to another key source of uncertainty associated with carbon and nutrient exports because they under-sample and underrepresent short-duration, high-flow events. High flow events represent critical times or ‘hot moments’ of carbon export, and their exclusion may substantially bias estimates of material transport [45, 90]. These high flow events are innately challenging to characterize and capture with traditional grab sampling approaches commonly used in river export studies [91], particularly in remote Arctic regions [92]. Therefore, there is a need for both higher-frequency and longer duration water quality monitoring of Arctic headwaters to address both sources of uncertainty in measuring concentration and discharge.
In terms of studying watershed biogeochemistry with more temporal resolution and duration, robust in situ water chemistry sensors for DOC and nutrients exist [87, 93–95] and can be used to meet these monitoring needs in Arctic rivers. In recent years, the advent of sensor technology has allowed increasingly frequent measurement intervals of carbon and nutrients, and the ability to continuously monitor stream-water chemistry such that episodic events can be consistently captured across many continuous months and years [86, 94, 96–103]. However, if in situ water quality sensors are unavailable or infeasible for Arctic scientists trying to conduct watershed carbon and nutrient export budgets, striving to collect higher-frequency sampling of paired concentration grab samples and river flow measures should be a goal, with particular emphasis on capturing the dynamics across a range of discharge across the hydrograph.

Our case study quantifying DOC and NO$_3^-$ exports in the Kuparuk used high-frequency monitoring data collected with in-situ water quality sensors deployed across the 2017, 2018, and 2019 flow seasons (detailed methods in the Supplement). Our study captured temporal variation within the critically understudied hydrologic periods of the Kuparuk watershed—the shoulder seasons and high flow events. We present the temporal trends of precipitation, discharge, and DOC and NO$_3^-$ concentrations for the Kuparuk headwaters in figure 4. Based on the monitoring time frames of mid-May (2017) or mid-June (2018, 2019) through late-September, the Kuparuk River exported 297,000 kg DOC in 2017, 420,000 kg DOC in 2018, and 260,000 kg in 2019 (figure 4(D)). For NO$_3^-$, the Kuparuk exported a total of 3900 kg in 2017, 15,800 kg in 2018, and 8,770 kg in 2019 (figure 4). After accounting for differences in monitoring period length, the Kuparuk DOC yield averaged 25 kg km$^{-2}$ d$^{-1}$ in 2017, 50.7 kg km$^{-2}$ d$^{-1}$ in 2018, and 31.4 kg km$^{-2}$ d$^{-1}$ in 2019. NO$_3^-$ yield averaged 0.33 kg km$^{-2}$ d$^{-1}$ in 2017, 1.9 kg km$^{-2}$ d$^{-1}$ in 2018, and 1.1 kg km$^{-2}$ d$^{-1}$ in 2019. The riverine budget is presented by month, total export, and cumulative mass export in figures 5 and 6.

Unlike previous studies that have observed the largest proportion of annual DOC flux during snowmelt, we found that by extending the monitoring into the shoulder seasons, the largest portion of annual flux occurred later in the flow season, primarily associated with rain events (figure 4). While the dominance of snowmelt versus late shoulder season rain on DOC export patterns varied by year, the general pattern of high exports in August was consistent across all three monitoring years. DOC concentration was highest during the May and June snowmelt period in 2017 (figure 5(A)), consistent with many previous Arctic studies [49, 50, 104, 105]. However, the total exports in May and June for that year only accounted for 18.8% and 15.8% of total measured DOC and NO$_3^-$ export, respectively. Later in the 2017 flow season, July (23.8%) and August (25.8%) accounted for...
the majority of total DOC export, with the rarely sampled September period exporting the remaining 17.8% (figure 5(A), middle row). July through September was when DOC concentration was lowest, but water discharge increased dramatically due to increased precipitation. This general pattern was consistent across all study years, where cumulative DOC export coincided with short, high-discharge periods from either the snowmelt period or precipitation events (figures 5(A)–(C), bottom row). Concurrently, NO$_3^-$ concentration was lowest in May and August, but higher in June, July, and September (figure 6(A)). Total monthly NO$_3^-$ export generally increased across the flow season and was lowest in May and June, peaking in July and August (figure 6(A)).

While these estimates represent only three flow seasons of export for the Kuparuk headwaters, they suggest that the shoulder seasons represent a significant proportion of seasonal flux, despite their omission from both biogeochemical and hydrologic studies (figure 7). Further, our analysis highlights that precipitation-induced high flow events during the late flow season dominated the overall DOC export from the Kuparuk headwaters. For example, in the 2017 flow season, if we had monitored only the average study dates (May 25–August 27) as most prior studies have done, we would have underestimated total DOC export by 24%. Also, if we had not captured the storm-event driven DOC export, we would have underestimated total DOC export by 49% (figure 7(B)). The underestimations for DOC were even greater in 2018 and 2019 (figure 7(B)). Again, while the snowmelt period represented a large proportion of DOC and NO$_3^-$ export in 2017 (34% and 30%, respectively), more nuanced biogeochemical flux behavior associated with rain events emerges with extended field season and high-frequency monitoring. The role of rain events is particularly important because increased rain during the thaw season is one projected impact of climate change in the study region [106]. Overall, this case study shows that the incorporation of high-frequency in situ river chemistry observations represents an opportunity to extend the field season beyond what has been previously monitored, reveals new processes driving solute export, and lowers uncertainty in the export estimates relative to less-frequent grab sampling [86].

1.4. Toward a more complete understanding of river solute exports in a changing Arctic

Both of our assessments of the environmental literature and our use of high-frequency water chemistry for the Kuparuk headwaters challenge current conventions on the timing and magnitude of nutrient and carbon exports from permafrost-underlain Arctic landscapes, particularly during the late season. These temporal gaps in Arctic ecohdrology parallel similar blind spots in terrestrial Arctic ecology, which are increasingly being identified and filled [107]. This demonstrates how the temporal gaps in Arctic
hydrochemistry and river budget assessments provide numerous opportunities to improve our understanding of how permafrost ecosystems may respond to climate change. Below, we describe several considerations that should be integrated with current and future Arctic sampling and monitoring efforts.

1.4.1. Incorporating high-flow events and changing precipitation regimes.

The fate of carbon and nutrients liberated by permafrost thaw depends largely on Arctic hydrology [31, 32], which influences both organic and inorganic nutrient transport from landscapes to river networks and nutrient availability in aquatic ecosystems [23, 30, 52, 70, 108]. Concurrently, key processes affecting landscape inputs of DOM and DON/DIN are related to increased precipitation and permafrost thaw [109–111]. We propose that the current understanding of DOM/DOC export is not sufficient to predict responses to warming and hydrologic change at high latitudes, as sampling strategies do not often account for the influence of high-flow events nor the late flow season. Further, the integration of biogeochemistry and hydrology represents a major knowledge gap for Northern latitudes [112]. From a hydrodynamic perspective, it is known that the majority of DOM is flushed from landscapes and transported through river networks during high flow events [45, 82, 113], but these events have simply been under-measured in Arctic headwaters (this study), and in other Arctic watersheds that span diverse landscape characteristics [67]. The incorporation of high-flow events into ecosystem budgets is innately tied to capturing the variability in discharge relative to variation in DOM or DIN concentration. For example, in our study watershed, discharge has historically varied over many orders of magnitude, while concentrations of DOM and DIN fluctuate between far fewer orders of magnitude (SI figure 2). Hence, when focusing monitoring efforts, particularly when high-frequency biogeochemical sensors are not feasible, we recommend focusing efforts on (1) expanding the temporal duration of field efforts, (2) high-frequency monitoring of discharge which is complex and expensive high-frequency biogeochemical monitoring, and (3) focusing biogeochemical grab samples across a range of discharge conditions, especially high flow events.

In general, for most temperate watersheds, hydrologic events including precipitation and snowmelt mobilize DOM that is rapidly shunted downstream as water velocity increases and water residence time decreases [90]. In other words, high flow events drive the majority of downstream export, with the greatest exports occurring at relatively short timescales. In temperate forested headwaters, for example, up to 60% of annual dissolved organic carbon (DOC) exports occur during rapid, high-volume hydrologic events that constitute only 5% of the year [89]. It is therefore not surprising that in our case study of the

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**Figure 5.** Monthly mean (A) DOC concentrations (mg l⁻¹), (B) total monthly export (kg), and (C) cumulative export (kg) for the 2017, 2018, and 2019 monitoring seasons for the Kuparuk River.
Kuparuk headwaters, we found that the majority of flow season export occurred in July and August, coinciding with several large rain events that drove pulses of DOC (figures 4–5). While the dataset we present spans only three flow seasons for one watershed, it is further evidence that watershed hydrodynamics may function in permafrost influenced watersheds with the same general transport-limitation behavior of pulsing and shunting of DOC seen in temperate watersheds [45, 110].

Our use of high-frequency observations is an example of an opportunity to frame the predicted changes solute export from Arctic watersheds and possibly leverage current hydrodynamic frameworks developed outside of the Arctic. For example, given that rain events in the Arctic are expected to increase in frequency and intensity [36], understanding riverine fluxes during high flow events, and incorporating these critical export periods into ecosystem budgets and models, will become increasingly critical under the current climate change scenarios. Indeed, rain in the Arctic has already shown increasing trends in recent decades [34, 114, 115], with a mean sensitivity of 2%–4.5% increase of rain with every degree of warming [34, 106, 116]. Therefore, as a result of climate change, we should expect an altered season length, with spring snowmelt beginning earlier and an extended flow season [30, 34, 117]. Altered seasonality may result in an asynchrony between terrestrial plant growth and the activity of instream processes, decoupling terrestrial and stream ecosystems in the early spring and especially in the late fall, favoring higher primary production, respiration, and nutrient turnover for longer periods of the year [118, 119]. The resulting decoupling could have important influences on the amount and the nature of material fluxes from the Arctic landscape to the Arctic Ocean, which could be further released during high flow events. Under scenarios with a wetter late season, the proportion of DOM shunted from headwaters to coastal ecosystems will likely increase, regulating key components of the global carbon cycle far from the headwater source. These various interacting ecological processes and their potential changing synchrony maybe be best observed by using high-frequency in situ monitoring of river solutes will be key which can capture seasonal and event signals generated by the biogeochemical source and sink processes occurring upstream in the watershed [61, 62, 120, 121].

1.4.2. Monitoring river chemistry across the entire flow season as the shoulder seasons get longer.

River exports regulate key components of downstream aquatic and terrestrial biogeochemical cycles, and the impact of downstream fluxes depends strongly on the timing and magnitude in addition to the abundance of coupled constituents [122]. Our 2017 solute flux case study highlights the importance of capturing the whole season with respect to estimating carbon and nutrient export and from
Arctic rivers. The shoulder seasons of May and late August and September have been relatively under-sampled [123, 124], and the majority of studies have occurred at or near baseflow conditions. To be clear, we do not argue for a diminishing influence of the spring snowmelt; the snowmelt period will likely continue to introduce a substantial amount of terrigenous DOM/DOC into river networks. Rather, we contend that the potential for later-season DOM-/DOC pulse from the headwaters during high-flow events may be significant, and the fate of this carbon is still unknown. Therefore, whenever possible, we recommend incorporating high-frequency monitoring stations in Northern high-latitude monitoring efforts and advocate for ongoing monitoring efforts to be extended to include more of the shoulder seasons. Moreover, the extension of the field season and continued long-term observations will likely require the support of funding sources and the commitment from scientists across ecologic disciplines [125, 126].

Additionally, Arctic riverine frameworks must also recognize changing Arctic DOM composition, reduced processing mechanisms, and increasing hillslope connectivity that may occur as a result of shifting hydrologic events and seasonality. The lability (i.e. biodegradability) of DOM is a key regulator of ecosystem function and linked to molecular structure and other environmental variables such as temperature, vegetation structure, and microbial activity [127]. DOM exported from Arctic rivers during the snowmelt period has been relatively labile [65, 70, 128], and increasingly refractory during the late flow season [65, 129]. However, DOM quality is likely to shift with response to changing seasonality [130–132], permafrost thaw and thermokarst frequency [53, 56, 133, 134], disturbance [48, 135–139], landscape vegetation shifts [140–142], and increasingly variable precipitation regimes [36, 143]. Larger storm pulses, enhanced subsurface flow, and reduced instream processing may lead to enhanced lateral and longitudinal solute flux by effectively reducing the exposure time of transported solutes to both terrestrial [46, 144] and instream removal mechanisms [16, 90, 145]. A wet late flow season therefore represents a large potential pulse of organic matter into stream networks. While these fluxes have important implications for net metabolism and nutrient cycles of both directly downstream as well as coastal systems.

Figure 7. Flow season riverine budgets of (A) DOC and (B) NO$_3^-$ estimated for the total season measured empirically (dark grey bar, all dates for 2017, 2018, and 2019), and then the summed mass over the average dates (black bar, May 25–August 27), average but with no storms (light grey bar), biogeochemistry (yellow bar, May 21–September 3), and hydrology (blue bar, May 26–August 10) mean study dates. Estimated percent mass captured relative to the total annual budget is noted in white text. Note that ‘average’ period is based the meta-analysis results from the range of ecological studies occurring in the Kuparuk headwaters (see figure 2).
[146], they have largely been ignored in carbon and nutrient budgets for Arctic ecosystems. Another key knowledge gap is associated with defining the different potential fates of DOM exported at the end of the flow season versus the snowmelt period and early flow season. Because accurate estimates for riverine carbon and nutrient exports are critical for global and regional Arctic carbon and nutrient budgets, we must continue to address the role of hydrologic events and how DOM is transported and transformed during its downstream journey, particularly during the relatively understudied shoulders of the flow season.

1.5. Moving outside of the river channel
We have focused this piece primarily on biogeochemical and hydrologic feedbacks and processes within a well-studied river network as a way to highlight the broad need for improved understanding of the ecological changes in Arctic landscapes outside of the middle of the thaw season (e.g. figure 2). We have therefore presented a river-focused road map for where we are, what we are missing, and how we can move forward towards interdisciplinary understanding of Arctic biogeochemistry by focusing on a research flagship Arctic headwater. However, we recognize that river networks represent only some components of the landscape. While we have identified clear temporal gaps in understanding of biogeochemistry and hydrology in the Kuparuk, our approach underscores another primary challenge: integrating understanding across ecological disciplines (figures 2(B)–(G)). Based on the topical meta-analysis, the greatest research efforts have often been temporally out of phase with each other (e.g. microbial versus hydrologic studies, figure 3(B)). Furthermore, efforts to expand understanding of Arctic ecosystems must be viewed holistically, where river biogeochemistry and hydrology are intrinsically linked to studies related to landscape vegetation, temperature and active layer dynamics (figure 2). Therefore, even if we are able to measure more of the shoulder season stream biogeochemical and hydrologic responses, it will be challenging to explain stream conditions and fluxes without perspectives and predictions from other ecological disciplines. In other words, we stress that simple analyses like the one presented in this paper offer a window into major potential fates of DOM exported at the end of the flow season versus the snowmelt period and early flow season. Because accurate estimates for riverine carbon and nutrient exports are critical for global and regional Arctic carbon and nutrient budgets, we must continue to address the role of hydrologic events and how DOM is transported and transformed during its downstream journey, particularly during the relatively understudied shoulders of the flow season.

2. Conclusions
In the coming decades, the Arctic will experience significant changes in ecological structure and function: warming Arctic ecosystems will be altered by extended thaw seasons, increased hydrologic extremes, and permafrost degradation. The expected consequences of changes to Arctic carbon and nutrient budgets will have cascading implications at local, regional, and global scales [23,148]. Now is the time to identify and address the knowledge gaps that limit understanding of Arctic ecosystem structure and function. In other words, we call upon our fellow researchers to ask: What ecological processes and consequences are we missing by giving early and late Arctic seasons the ‘cold shoulder’? Though we have taken a riverine biogeochemical flux perspective and proposed two important considerations for present and future watershed monitoring regimes, we recognize that understanding a changing Arctic will require integrating new datasets, refined perspectives, and continued funding for studying a new Arctic. Therefore, we also stress that while ecological dynamics during the ‘shoulder’ seasons represent a major data gap for Arctic ecosystems, it is also an exciting opportunity to improve understanding of Arctic systems across ecological disciplines [147,149].

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Author statement
A J S and J P Z conceived of the presented manuscript. J P Z, B W A, F I, and W B B designed the high-frequency sampling regime. All authors contributed to the field, lab, and data analysis that is presented in this manuscript. A J S performed the meta-analysis and high frequency data analyses. All authors contributed to and approve of the submitted version.
Data availability

The data that support the findings of this study will be openly available at the following URL/DOI: (https://arc-lter.ecosystems.mbl.edu/2017-2019zarnetskekupchem.)

Social media statement

Ignoring the Arctic shoulder seasons (early spring and late fall) misses crucial transitions and underestimates material transported by Arctic rivers.

ORCID iDs

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