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WHY MONITOR CARBON IN HIGH-ALPINE STREAMS?

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ABSTRACT. In this short communication, we report on dissolved organic and inorganic carbon concentrations from a summer stream monitoring campaign at the main hydrological catchment of the Tarfala Research Station in northern Sweden. Further, we place these unique high-alpine observations in the context of a relevant subset of Sweden's national monitoring programme. Our analysis shows that while the monitoring programme (at least for total organic carbon) may have relatively good representativeness across a range of forest coverages, alpine/tundra environments are potentially underrepresented. As for dissolved inorganic carbon, there is currently no national monitoring in Sweden. Since the selection of stream water monitoring locations and monitored constituents at the national scale can be motivated by any number of goals (or limitations), monitoring at the Tarfala Research Station along with other research catchment sites across Fennoscandia becomes increasingly important and can offer potential complementary data necessary for improving process understanding. Research catchment sites (typically not included in national monitoring programmes) can help cover small-scale landscape features and thus complement national monitoring thereby improving the ability to capture hot spots and hot moments of biogeochemical export. This provides a valuable baseline of current conditions in high-alpine environments against which to gauge future changes in response to potential climatic and land cover shifts.

Key words: carbon, monitoring, alpine, streams

Introduction

Designing and maintaining an adequate water monitoring programme is difficult (Lovett *et al.* 2007). Since the chemicals and solutes of interest to regulators, society and researchers can differ significantly and change over time, those agencies mandated with maintaining stream water quality monitoring programmes face a daunting task. This task is often made more difficult by decreased budgets bringing about decreases in active monitoring of streams (Lovett *et al.* 2007; Bring and Destouni 2009). Among the many constituents exported from land to sea in the Arctic, inorganic nutrients and organic matter are of particular interest as potential resources supporting biological production in coastal waters (McClelland *et al.* 2014). Further, organic carbon (and increasingly inorganic carbon) in streams has attracted much attention in recent years since it is a significant part of the local as well as global carbon cycle directly influenced by atmospheric deposition, fluvial microbial communities, and climatic changes (Cole *et al.* 2007; Battin *et al.* 2008; Raymond *et al.* 2013). While stream inputs have traditionally been seen as a minor contribution to arctic coastal ecosystems, recent work highlights their potential role in seasonal biogeochemistry variations in arctic coastal waters (Holmes *et al.* 2012; Tank *et al.* 2012). Still, linkages between streams and carbon transport, however, are complex (Jantze *et al.* 2013; Winterdahl *et al.* 2014) such that carbon movement across the terrestrial–aquatic interface, along with its fate in inland waters and feedbacks with climate change, is still by-in-large poorly understood (Battin *et al.* 2009; Laudon *et al.* 2012). To fully understand these linkages requires monitoring and observations of aquatic carbon concentrations aligned with our ability to represent coupled hydrological and biogeochemical processes. This is particularly true if our goal is to implement parsimonious models to simulate stream chemistry dynamics (Lyon *et al.* 2010; Birkel *et al.* 2014) that can allow for estimations in a changing climate.

In arctic and sub-arctic landscapes, it can be argued that there is rather good understanding of seasonal and annual water discharge as a

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consequence of long-term monitoring and large-scale modelling (Lammers *et al.* 2001; Syed *et al.* 2007). Our understanding of constituent export (McClelland *et al.* 2014), however, is potentially limited due to a relative lack of spatial and temporal information on water chemistry (Holmes *et al.* 2000; Bring and Destouni 2009). While larger river systems have received much attention (Raymond *et al.* 2007), logistical challenges associated with field campaigns have generally limited field-based studies of water chemistry in northern landscapes. There is clearly a shortage of detailed observational data available for organic and inorganic carbon export from small-scale arctic and sub-arctic systems (Giesler *et al.* 2014; Jantze *et al.* 2015). The remoteness and inaccessibility of arctic and sub-arctic environments together with technical challenges in measuring both lateral and vertical carbon fluxes of streams (Cole *et al.* 2007) have contributed to the current lack of observations from sub-arctic headwaters. As such, our current state of knowledge of dissolved carbon processes across northern landscapes relies heavily on the stream monitoring networks maintained by government agencies at national scales. This can be worrisome since the motivation for these stream monitoring programmes (and the location of monitoring sites within the landscape) may not have had carbon as a central focus given the relative 'newness' of interest by society and researchers in climate change. We cannot accurately assess potential changes in constituent fluxes until we have established a contemporary baseline (McClelland *et al.* 2014).

In this regard, northern Fennoscandia offers a significant platform for monitoring arctic-relevant constituents across a range of ecosystems and geophysical environments with relatively easy accessibility. For example, few regions globally offer a range of permafrost conditions that are easily accessible while at the same time on the cusp of change (Sjöberg *et al.* 2015). In addition, northern Fennoscandia, with its large latitudinal and altitudinal temperature and precipitation gradients (van der Velde *et al.* 2013), offers a region to monitor coupled hydrological and biogeochemical conditions thereby providing a strong testbed for field-based exploration of climatic change impacts. In this note we leverage that 'nearness' (relative to northern Russia or Canada) and report on stream water total organic and inorganic carbon concentrations at the *Tarfala Research Station* (*TRS*) during a summer monitoring campaign. This short monitoring campaign is placed in the context of a relevant subset of Sweden's national monitoring for dissolved carbon. The goal of this comparison analysis is to highlight potential gaps in coverage of key environments and ecosystems (and therefore subsequent processes) relevant for Sweden and much of northern Fennoscandia. This makes a case for the potentially complimentary nature of the data available from research catchments and highlights the need for networks to connect researchers with these data.

Methods

Tarfala Research Station campaign and data

TRS's main hydrological catchment (e.g. Dahlke *et al.* 2014) has an area of 21.7 km^2 within the high-alpine environment (18° 37′ 51″ E, 67° 53′ 55″ N) situated in the Scandinavian Mountains in northern Sweden. The catchment is located in the discontinuous permafrost zone (Peel *et al.* 2007) with an altitude range between 980 and 2097 m a.s.l. The catchment's main valley is dominated by glaciers that cover 30% of the catchment area, bedrock outcrops and glacial tills. Alpine heath vegetation is found in the valley bottom where the soil cover is shallow. Based on data available from the Swedish Meteorological and Hydrological Institute the average air temperature at the TRS for 2011 was –5.8°C and the precipitation was 1489 mm.

During the 2011 summer season (20 Jun. to 10 Sep.), daily instantaneous stream water samples were collected from the main stem of the Tarfalajokk stream at the catchment outlet. Samples were collected at approximately 5 pm local time using sterile 60 ml HDPE wide-mouth Nalgene bottles. Samples were kept refrigerated until laboratory analysis at the Swedish University of Agricultural Sciences in Umeå, Sweden. Samples were analysed for their *total organic carbon* (*TOC*), and *total inorganic carbon* (*TIC*) within maximal four weeks after field collection using a TOC-V$_{\mathrm{CPH/CPN}}$ Shimadzu Total Organic Carbon Analyzer (Shimadzu Inc., Kyoto, Japan).

Swedish national monitoring sites and data

To facilitate comparison, only a subset of all Swedish national monitoring sites was considered here with an eye towards regions with comparable climates and similar landscape types. Carbon concentration data were accessed from the national environmental monitoring programme of fresh water hosted by the Swedish Agriculture University.[1]

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[1] http://www.slu.se/vatten-miljo

Table 1. Summary of basic catchment properties including coordinates, years of sampling record considered in this study, catchment drainage area, average annual *total organic carbon* (*TOC*) concentration over the period of record considered, annual average precipitation and annual average temperature (both according to Climate Research Unit dataset) ranked by catchment area. The relevant information for the Tarfala Research Station catchment are given for comparison (italics)

Site name	Lon.	Lat.	Years	Area (km^2)	TOC (mg L^{-1})	Precip. (mm)	Temp. (°C)
Höjdabäcken	16° 55′ 26″	64° 02′ 4″	2001–2013	5	10.0	585	1.4
Lill-fämtan	13° 07′ 9″	60° 50′ 33″	2001–2013	6	10.6	731	4.1
Oradbäcken	13° 29′ 57″	61° 10′ 16″	2009–2013	8	11.2	828	2.1
Laxtjärnsbäcken	19° 05′ 16″	65° 47′ 9″	2001–2013	11	3.8	550	0.3
Bergmyrbäcken	19° 05′ 4″	65° 35′ 32″	1995–2013	15	6.6	581	0.1
Akkarjåkka	19° 26′ 24″	67° 51′ 50″	1995–2013	21	2.5	561	−1.6
Tarfala	*18° 37′ 51″*	*67° 53′ 55″*	–	*21*	–	*1489*	*−5.8*
Kärmsjöbäcken	16° 48′ 21″	63° 52′ 03″	1997–2013	25	10.1	631	1.9
Bjurbäcken	20° 23′ 22″	64° 40′ 33″	1998–2013	43	18.8	539	3.1
Lekarån	13° 44′ 16″	63° 4′ 30″	2007–2013	83	1.4	711	1.9
Viepsajåkka	17° 39′ 49″	66° 28′ 41″	1995–2013	88	3.1	636	−1.8
Skansnäsån	16° 03′ 9″	65° 16′ 16″	2007–2013	91	4.5	721	−0.4
Alep Uttjajåkka	18° 55′ 33″	66° 36′ 8″	1997–2013	100	5.1	612	−1.3
Hökvattsån	14° 52′ 50″	63° 51′ 31″	2008–2013	104	6.9	583	2.9
Ostvik	21° 04′ 3″	64° 54′ 6″	2001–2013	149	13.0	539	3.3
Mattjåkkbäcken	18° 14′ 58″	65° 10′ 25″	2007–2013	156	10.1	526	1.0
Ljusnan Funäsdalen	12° 33′ 59″	62° 33′ 18″	1987–2013	295	2.3	821	0.0
Muddusälven	20° 07′ 29″	66° 45′ 57″	2001–2013	452	5.7	525	−0.7
Kukkasjärvi	23° 19′ 6″	66° 06′ 49″	2001–2013	456	12.2	566	1.9
Stormyrbäcken	16° 16′ 5″	62° 15′ 34″	1987–2012	499	1.136	650	2.8
Abiskojokk	18° 46′ 15″	68° 21′ 24″	1987–2013	565	1.5	942	−3.7
Vapstälven	14° 31′ 15″	65° 26′ 34″	2007–2013	580	2.2	878	0.3

As a first result, it should be noted that only TOC concentration data were available and no data were reported for inorganic carbon within this database. Rather, alkalinity is reported; however, estimation of inorganic carbon and its speciation from alkalinity can be associated with large uncertainties, especially in acid or low-alkalinity streams (Wallin *et al*. 2014). Considering the TOC concentrations, this database contains stream water chemistry data for more than 200 monitoring locations ranging in scale from 0.19 km^2 to more than 47 000 km^2 in area. To simplify, we first trimmed down our selection of sites to only the boreal and tundra environments of Sweden. Specifically, we used Köppen's climate classifications (Peel *et al*. 2007) to select catchments containing more than 80% area within continental subarctic or boreal (taiga) climates (codes Dfc, Dwc and Dsc) and/or polar and alpine tundra climates (code ET). In addition, to avoid the impacts of extremely large systems and extensive flow regulation, we considered only catchments smaller than 600 km^2 in area (Table 1). For the resulting 21 stations, long-term monthly average TOC concentrations were calculated from available data. All data available were included rather than defining common overlapping periods since we are not inter-comparing across these sites but rather using them for a contextual assessment. Simply put, we are not trying to cover all monitoring locations at all spatiotemporal scales here; rather we want to provide a relevant context for our short time monitoring at TRS. We acknowledge that this places some limits on the analysis to be considered (and potential conclusions that can be drawn).

In addition to the stream data, spatial data were compiled for each monitoring location. *Digital elevation models* (*DEMs*) at resolutions of 50 × 50 m^2 were downloaded from the Swedish University of Agricultural Sciences.[2] Land cover raster maps (Corine land cover 2006) at resolutions of 100 × 100 m^2 were accessed from the European Environmental Agency.[3] The DEMs were used to delineate the catchments using the hydrology toolkit within ArcGIS 10.0 (ESRI). The delineated catchments were used to derive the land cover composition per catchment. Land cover was divided into the following main classes: forest, wetland, scrub/herbaceous vegetation, open land, and other (which included arable land, artificial, non-agricultural vegetation, heterogeneous agriculture lands; industrial, commercial and transport lands;

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[2] http://maps.slu.se

[3] http://www.eea.europa.eu/data-and-maps/data

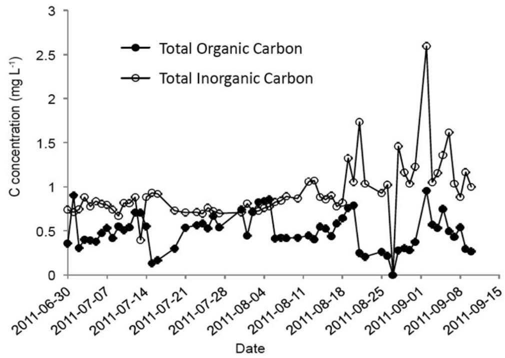

Fig. 1. Total organic carbon and total inorganic carbon concentrations observed in the stream water draining from the main Tarfala Research Station catchment during summer 2011.

inland waters; mine, dump and construction lands; pastures; and urban fabric according to the Corine land cover standard). The open land cover class is coincident with high alpine or tundra environments in Fennoscandia.

Results and discussion

Representativeness of current monitoring and high-alpine streams

We begin by considering the Tarfalajokk stream sampling campaign. There is clear consistency over the sample period with regards to low TOC concentrations (Fig. 1). This consistency is echoed in the TIC concentrations for the first part of the sampling; however, there is an increasing trend in TIC concentrations later into the campaign. In addition, there are increased relative variability in both TOC and TIC concentrations comparing the beginning and end of the sampling campaign. These increases in TIC concentrations and increases in variability for both constituents are consistent with flow pathway estimates and the mechanisms outlined in Dahlke *et al.* (2014). Specifically, they coincide with reduced water storage capacity within glaciers, increased transport of rainwater to the stream, and larger probability of connections between mineral soil water storages and the stream system as we move through the summer season. From a research perspective, these initial data beg to be placed in a relevant context. But, how well is this type of landscape represented in our current monitoring to provide such a context?

Sweden provides a good and rather representative coverage of the region’s physiographic and land cover diversity – at least with regards to forest coverage (Fig. 2). Given the importance of forested lands to industry and forestry and the past decades of acid rain research (e.g. Bishop *et al*. 1990) along with the general ubiquity of boreal ecosystems in Sweden, this representativeness of forest coverage is to be expected. Of course, a consequence of this is that there is a potential under-representation of other types of land cover – specifically high alpine or tundra environments – which can have significant impacts on nutrient (Hood *et al*. 2003b) and carbon cycling (Hood *et al*. 2003a; Singer *et al*. 2012) for downstream systems. This finding is consistent with that of Bring and Destouni (2009), and more recently Bring and Destouni (2014), where areas of tundra and continuous permafrost were shown to be strongly under-represented both with regards to carbon and streamflow monitoring. Further, Bring and Destouni (2014) point out that while northern European monitoring may be considered relatively better compared with other northern regions with regards to representation of major eco-regions, there is a considerable bias towards near ocean (coastal) catchments which are mutually exclusive to the high alpine environments in Sweden.

Interestingly, or perhaps as should be expected given the connections between aboveground biomass and TOC, the monitoring locations cover a good range of TOC concentrations (Fig. 3). The monthly average TOC concentrations from the July to September 2011 TRS sampling campaign fell well outside and below this range. This is in agreement with previous work in arctic and subarctic rivers where dissolved inorganic carbon is a major component of stream carbon, accounting for as much as 70% of the dissolved carbon flux (Striegl *et al.* 2007). In fact, most large rivers are richer in dissolved inorganic carbon than TOC (Cooper *et al.* 2008; Giesler *et al.* 2013). Further, the low TOC concentrations in the TRS sampling campaign demonstrate the need to monitor dissolved carbon from these unique landscapes since they are not similar to anything currently covered in the national monitoring programme.

Sweden, like many countries, has no national efforts for monitoring in alpine/tundra environments as unique systems (moreover as landscape end members). Rather, these landscapes are integrated within the large-scale coverage obtained through the national-scale efforts. This large-scale coverage in monitoring is of course vital as it underpins our mechanistic understanding and forms the cornerstone to estimating future dissolved carbon cycling along the aquatic conduit

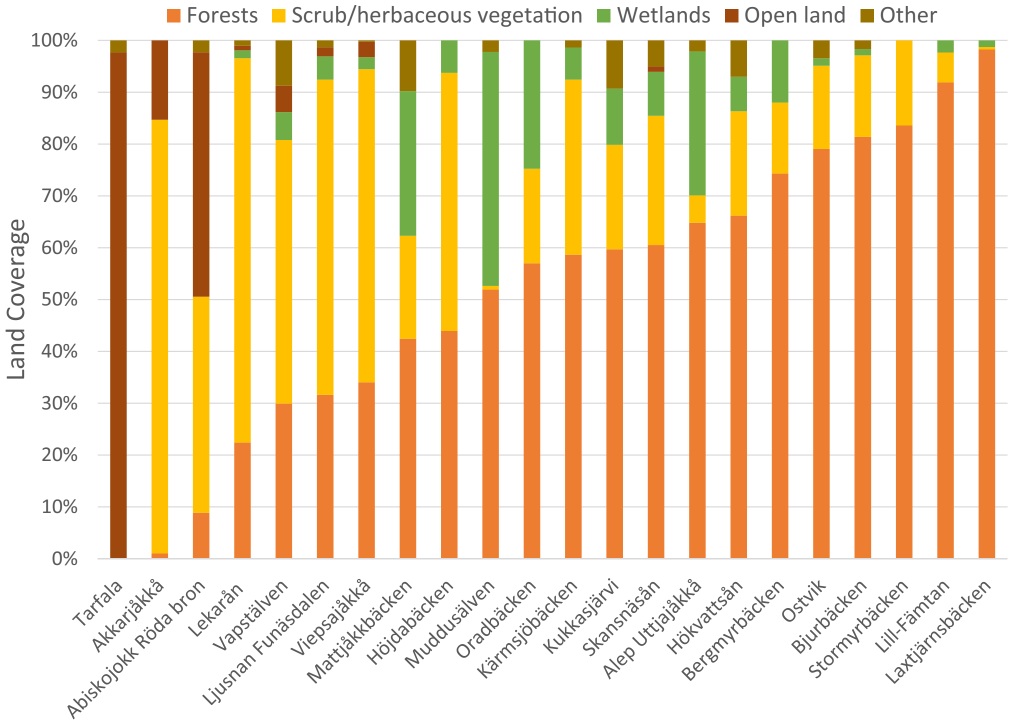

Fig. 2. Land cover distributions ranked by forest coverage of 21 national monitoring locations for northern Sweden according to Corine classification maps. The land cover distribution for the Tarfala Research Station catchment is included for reference.

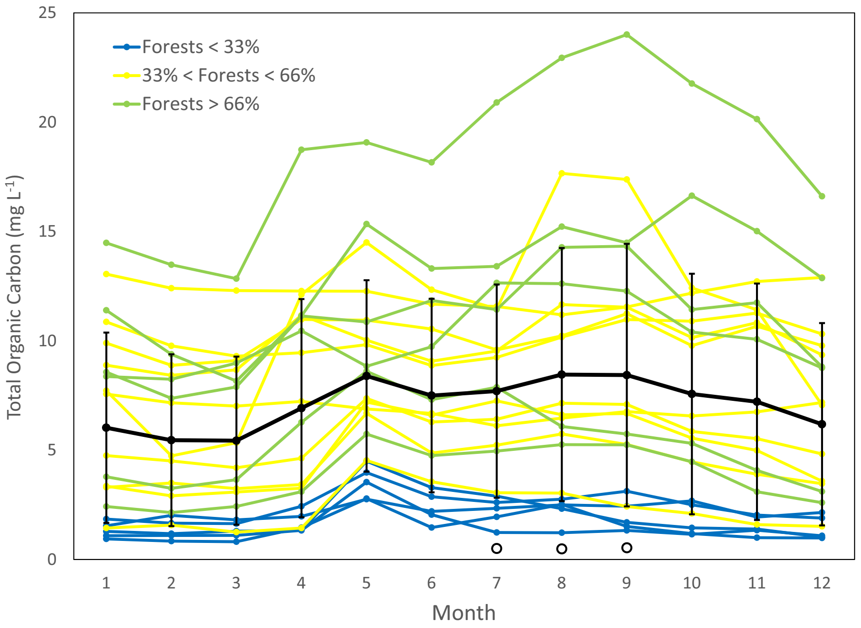

Fig. 3. The range of average monthly total organic carbon concentrations for the 21 monitoring locations considered nearby the Tarfala Research Station. The black line and symbols show the average across the sites with error bars indicating one standard deviation. The monthly average total organic carbon concentrations at Tarfala Research Station during 2011 are indicated as open circles.

(Cole *et al.* 2007). Still, TOC concentrations in smaller streams or export from more homogenous landscape components (such as alpine and tundra environments) should not be overlooked. This is particularly important when attempting to assess impacts of climatic changes as we must consider not only land coverage impacts but also potential shifts in hydrology and how water interacts with geology. For example, previous work by Jantze *et al.* (2015) in the Abiskojokka catchment, located near to the TRS catchment in sub-alpine northern Sweden, indicates that neither vegetation coverage nor lithology alone can explain the concentrations and mass flux rates of dissolved carbon. The study highlights the importance of studying lateral carbon transport through the landscape in combination with hydrological flow paths at small scales to establish a knowledge foundation applicable for expected carbon cycle and hydroclimatic shifts due to climate change (e.g. Mulholland and Hill 1997; Seibert *et al.* 2009) in these rapidly changing climates.

So, what are we missing?

The large-scale nature of national monitoring programmes may render us blind to the hot spots and hot moments associated with dissolved carbon transport (McClain *et al.* 2003). Considering the (at best) monthly sampling offered up via the national monitoring networks, it is not likely that the full dynamic ranges in carbon concentrations associated with high-flow events such as spring freshet are truly captured (Halliday *et al.* 2012). As such, the largest lateral flux of carbon from the landscape during spring flood is rather short lived and thus may be missed every year. Further, the spatial scales covered by national monitoring are likely too coarse for detecting important small-scale landscape features such as ‘cryptic wetlands’ and riparian zones in forests that provide hot spots of organic carbon (Creed *et al.* 2003) or geological variations with variable weathering rates that can provide hot spots of inorganic carbon production (Geisler *et al.* 2014). These limitations and missing features could be potentially significant for assessments of aquatic carbon dynamics during low flow conditions (Laudon *et al.* 2011). This inability to capture the true nature of the landscape mosaic in large-scale monitoring efforts highlights the need for detailed and smaller-scale monitoring. This can be seen in our current study in the complementary nature of the TRS data to the large-scale monitoring programmes (Figs 1 and 3).

In addition, we may be missing information on the full suite of carbon constituents exported from these high-alpine environments (and northern landscapes in general). While this was somewhat anticipated, it warrants further consideration – especially given the dynamic nature and projected future of high-alpine and northern landscapes. Dahlke *et al.* (2012) highlight the potential impacts of alteration in the fundamental mechanism behind annual flooding (e.g. snowmelt vs. rainfall) over the glaciated Tarfala valley and surrounding areas. These shifts in mechanism and dominant hydrological process can have large consequences for mineralization/weathering processes, soil formation (erosion) and biogeochemical fluxes across high-altitude environments, as these high-altitude and high-latitude systems often form the background concentrations of biogeochemicals and nutrients for waters flowing as the headwaters of tundra and taiga landscapes. Considering again the TOC concentration from the Tarfala research catchment (Fig. 1), it should be noted that while organic carbon is at a low concentration under current conditions, TIC concentration is comparatively high. Further, as flow pathways shift in the landscape under future climatic changes (Lyon *et al.* 2010) this proportioning between organic and inorganic carbon can become more skewed. This is significant since the balance between organic and inorganic carbon partly determines the net trophic state of an aquatic ecosystem and can have impacts on future ecosystem services of northern latitudes (Singer *et al.* 2012).

Concluding remarks

Taken altogether, our study highlights that the state of carbon monitoring in northern Sweden is sufficient for certain land covers or landscape types but potentially underrepresents others. A corollary to this is that the balance between organic and inorganic carbon monitoring is currently unsatisfactory (from the perspective of establishing an empirical baseline) in the national programme given the potential for future shifts in biochemical cycling and water flow within arctic and sub-arctic landscapes. We therefore conclude this study with a comment on motivations for future efforts to reconcile these aspects.

Clearly, the aforementioned strengths of the current national monitoring effort should be maintained. Fölster *et al.* (2014) describe the value of long-term national monitoring of surface waters for understanding environmental issues such as acidification and eutrophication but also to have the capacity to address new questions in the future. To justify such monitoring, we in the scientific community must demonstrate how the data made available through such initiatives help advance our understanding of the physical landscape as it evolves. To best do this, there is need to co-locate different observation types (such as streamflow and temperature) and coordinate our efforts with ongoing monitoring. It is likely that such co-location of monitoring with experimentation allows for targeting hot spots and hot moments potentially missed in the current national monitoring efforts. We should, thus, bolster ongoing large-scale monitoring efforts through connection with our detailed research monitoring.

While such a recommendation is not entirely new and it is clearly not entirely feasible to monitor everything, everywhere and all the time, focusing on a few key locations, such as is the plan of the Swedish Infrastructure for Ecosystem Science (SITES) network, might offer a path forward. However, this requires coordination of monitoring (similar infrastructure) and sampling procedures (methodology, time plans). To facilitate comparisons (syntheses) and modelling efforts, it is also crucial to make available relevant meta-data about laboratory procedures, such as detection limits, resolution, accuracy and precision. As such, while network efforts like SITES are clearly positive for a good understanding of the hydroclimatic and biogeochemical processes at the different landscape end members, there is need for consistency and coordination throughout the programme.

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