

Northern landscapes in transition; evidence, approach and ways forward using the Krycklan Catchment Study

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Abstract

Improving our ability to detect changes in terrestrial and aquatic systems is a grand challenge in the environmental sciences. In a world experiencing increasingly rapid rates of climate change and ecosystem transformation, our ability to understand and predict how, when, where and why changes occur is essential for adapting and mitigating human behaviors. In this context, long-term field research infrastructures have a fundamentally important role to play. For northern boreal landscapes, the Krycklan Catchment Study (KCS) has supported monitoring and research aimed at revealing these changes since it was initiated in 1980. Early studies focused on forest regeneration and microclimatic conditions, nutrient balances and forest hydrology, which included monitoring climate variables, water balance components, and stream water chemistry. The research infrastructure has expanded over the years to encompass a 6790 ha catchment, which currently includes 10 gauged streams, ca. 1000 soil lysimeters, 150 groundwater wells, >500 permanent forest inventory plots, and a 150 meter tall tower (a combined ecosystem-atmosphere station; ICOS, Integrated Carbon Observation System) for measurements of atmospheric gas concentrations and biosphere-atmosphere exchanges of carbon, water, and energy. In addition to field infrastructures, the KCS has also been the focus of numerous high resolution multi-spectral LiDAR measurements. This large collection of equipment and data generation supports a range of disciplinary studies, but more importantly fosters multi-, trans-, and interdisciplinary research opportunities. The KCS attracts a broad collection of scientists, including biogeochemists, ecologists, foresters, geologists, hydrologists, limnologists, soil scientists and social scientists, and many others bringing their knowledge and experience to the site. The combination of long-term monitoring, shorter-term research projects, and large-scale experiments, including manipulations of climate and various forest management practices have contributed much to our understanding of the boreal landscapes functioning, while also supporting the development of models and guidelines for research, policy and management.

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1.0 Introduction

Water balance, carbon dynamics, and the ecological integrity of northern regions are expected to change in response to global warming. This, in combination with a growing human population, increased environmental pressure, and more intensive resource extraction will amplify the stressors imposed on terrestrial and freshwater resources in the north. Such changes may be gradual or abrupt, but in any case, the outcome is likely to be unexpected, owing to nonlinearities in catchment-scale storage and release of water, carbon, nutrients, and a wide range of additional processes. Already, a cascade of changes to northern landscapes have been observed in response to shorter and milder winters (Spence et al. 2015) and enhanced summer warming (Isles et al. 2016). Understanding and predicting how this trajectory toward a warmer climate will reshape the physical, chemical, and ecological properties of the natural environment at northern latitudes will be a critical challenge for the scientific community in the decades to come.

High quality empirical data of adequate spatial and temporal resolution are central for deciphering patterns, dynamics, and trends in environmental variables. Catchment hydrology, biogeochemical processes, and landscape carbon balance are inherently complex and often scale dependent, making reliable predictions of future conditions difficult (Laudon and Sponseller, 2018). Sound predictions are even more challenging in regions where appropriate empirical data to develop, test, and validate models are sparse. Despite the undeniable value of field observations and experiments, a transition from field-based empirical studies to model-only approaches has been an accelerating trend in environmental science (Burt and McDonnell, 2015). This trend is especially noticeable at northern latitudes, where the number of long-term research sites have declined rapidly during the last decades, leaving only a few locations with enough field data generated to answer the most pertinent questions about the future of our water resources (Laudon et al. 2017).

Most expected changes in response to anthropogenic forcing will be superimposed on natural variability that can mask responses and make changes difficult to detect and mechanistically explain. Unravelling the mechanisms responsible for various degrees of environmental perturbations in northern ecosystems therefore requires more than just basic monitoring information, standard models, and insights from other regions. The boreal region is dominated by nutrient limited forests and peatlands representing large carbon stores (Loisel et al. 2014) that contain at least a third of the Earth's soil carbon pool (Bradshaw et al. 2015). Despite their global importance and vulnerability to ongoing climate change, boreal catchments have been subject to comparatively little experimental, integrative, and process-oriented research in the past. This knowledge-gap is of concern, yet at the same time represent a tremendous opportunity for cutting edge research on global warming feedbacks to both the atmosphere and water resources.

Most stream hydrological and biogeochemical research is based on individual, well-studied catchments, or

alternatively on data from regional monitoring datasets. While a major advantage of small research catchments is the large amount of ancillary data that can provide mechanistic insights, a disadvantage is that the results are often based on limited replication and provide poor geographic representation. Conversely, a limitation of environmental monitoring is that data collection is often not designed to answer process-oriented questions, which can make it difficult to infer causal relationships. To overcome the constraints of both approaches, one way forward is to combine the strengths of these two approaches into a framework that promotes basic research in long-term monitored catchments (Tetzlaff et al. 2018), especially when they include several catchments of different scales and land-use (Laudon and Sponseller, 2018). The boreal landscape heterogeneity provides a unique template in this context because of the large spatial variability in the coverage of forest and peatlands that regulate much of the spatial and temporal complexity of soils, hydrology and biogeochemistry (Laudon et al. 2011; Fork et al. 2020). The study of stream networks also makes it possible to ascertain the influence of more seldomly studied headwaters to downstream ecosystems (Bishop et al., 2008)

Understanding the role of thresholds, tipping points, and other forms of nonlinearity is crucial for assessing the consequences of future environmental change. Detecting these responses requires field studies that go well beyond standard, disciplinary approaches. Instead, what is needed for solving future challenges is research infrastructures that combine field measurements from a multitude of disciplines in the same catchment. This type of effort goes well beyond what one research project or research group can achieve, and requires a well-coordinated infrastructure that can support and combine the collection of critical long-term monitoring data, provide large sets of ancillary empirical information, and host complementary long-term/large-scale experiments that are crucial to achieve mechanistic understanding of ecosystem responses to environmental change.

While long-term, process-based research at the landscape scale is clearly needed to address the influence of environmental perturbation on terrestrial and aquatic resources, few research sites exist that capture the spatial and temporal dimensions required. One existing example is the Krycklan Catchment Study (KCS), located in northern Sweden, which has provided a unique opportunity for integrated, process-based research in the boreal region for decades (Laudon et al. 2013). The over-arching objectives of KCS are to (1) provide a state-of-the-art infrastructure for experimental and hypothesis driven research, (2) maintain a collection of high quality, long-term climatic, biogeochemical, hydrological, and other environmental data, and (3) support the development of models and guidelines for research, policy and management. An important step in this direction is to make the field infrastructure even more visible for potential users at the same time as we make more of the field data accessible.

2.0 Site description

The Krycklan Catchment Study (KCS, www.slu.se/Krycklan) is located in the heart of the boreal landscape (64° 14' N, 19° 46' E), approximately 50 km northwest of the city of Umeå in northern Sweden (Laudon et al. 2013). The KCS includes 6790 ha land that comprises a mosaic of instrumented and well-studied forests, wetlands, and lakes, all drained and connected by a network of streams and rivers (Fig. 1). Over the past 35 years, the existing field research infrastructure has generated data resulting in approximately 1000 peer-reviewed publications, and over 110 PhD theses in diverse areas such as hydrology, biogeochemistry, carbon dynamics, climate change, geography, soil science, ecology, forestry, land-use history, and political science.

Forestry and peatland research began in area in the 1910s, with the first field station being built in 1923 at the Kulbäcksliden research park (Grip, 2015). Forest regeneration was a primary motivation for establishing the nearby Svartberget research station in the center of the KCS in 1979. The specific questions at that time were primarily related to microclimatic conditions after forest harvesting, nutrient limitation to tree growth, and forest hydrology. Ten years later, the role of acid deposition and natural acidity became the major water related research question at the site (Bishop et al., 1990). The combined focus on climate, forestry, and hydrology resulted in a wide range of high quality field measurements that are now of particular importance for documenting responses to current environmental changes.

Climate

An overall warming pattern is manifest in the long-term air temperature record from Svartberget from 1980 to present, but becomes even more visible when extending the time series back to 1891 by using the nearby Stensele site (Fig 2) for extrapolation. Air temperature has increased by about 3.5 °C since 1891 of which approximately 2.0 °C has occurred in the last 40 years (Mann-Kendall test, $p < 0.001$). The seasonal air temperature for winter, spring, summer and fall have all increased almost uniformly over the 40 years of monitoring by approximately 0.05 degrees °C per year (Fig 2b, Mann-Kendall test, $p < 0.01$ for all seasons), which among other consequences are manifested in the 50 year spring ice-off record for a lake just north of Krycklan (Fig 3b). Total annual average precipitation equals 623 mm, ranging from 446 (1994) to 918 mm (1982), with no statistical trend over the last 40 years. Of the precipitation, approximately 30% arrives as snow. The average snow water equivalents (SWE) for the 40 years of record is 180 mm, ranging from 64 (1996) to 321 (1988) mm. The 40-year average duration of winter snow cover is 167 days, but this is decreasing over time. During the first decade of measurement, the average date of initial snow cover was in early November; since then, this onset has been delayed by ~ 0.5 day yr^{-1} (Laudon and Löfvenius, 2016). However, the melting of snow in spring has experienced no significant trend, and on average occurs in late April. The long-term average annual runoff at a forest dominated catchment (C7; Fig 3a) has been 298 mm, with a minimum of 112 mm (1996) and maximum of 555 mm (2000) (cf Teutschbein et al., 2018).

Land-use history

Approximately 25% of the KCS has been protected for research since 1922, whereas the ownership of the remaining area is divided among private individuals and forest companies. Currently, forest covers 87% of the KCS and is dominated by Scots pine (*Pinus Sylvestris*) (63%) and Norway spruce (*Picea Abies*) (26%) with an understory of ericaceous shrubs, mostly bilberry (*Vaccinium myrtillus*) and lingonberry (*Vaccinium vitis-idaea*) on moss-mats of *Hylocomium splendens* and *Pleurozium schreberi*. *Sphagnum* spp. together with sparse coverage of sedges and dwarf shrubs dominate on open wetlands, which primarily can be categorized as acidic, oligotrophic, and minerogenic mires.

KCS has experienced relatively low levels of direct human influence. The current population of the area is approximately 1.2 people per km^2 . Historically, the human population was even lower and only hunting, fishing, and reindeer herding occurred until ca 1750 when the first village settlements were established. Prior to the early 1900's, mires constituted a major source of livelihood for farmers. In the KCS, this meant that up to 22% of the original mire area was used for hay harvest on mire meadows (Norstedt et al., in review), whereas only 3% were drained for more modern agriculture. Presently, only 1% of the original peatland areas are still used for agricultural purpose. Beginning around 1900, mires were drained to enhance forest wood production. As a consequence, about 40% of the original mire area is currently forested (Norstedt et al., in review). In addition, approximately 162 km (Hasselquist et al. 2020) of forest drainage ditches can be found within the KCS area, which can be compared with an approximately 180 km of naturally permanent streams (Ågren et al. 2015). Prior to the 1940s, selective cutting was the primary method used in forestry. Later, rotation forestry grew to dominate, involving mostly clear-cutting with subsequent planting of conifers (Norstedt & Laudon 2019).

Geological and physiographic setting

The KCS is located in the Svecokarelian orogenic belt, which traverses large parts of Sweden and Finland. The bedrock is dominated by 1.92-1.87 Ga old migmatized meta-greywacke or paragneiss, which consists of metamorphosed sediments once deposited outside the Achaean Baltic Shield. The numerous hills in the area with peaks up to 400 m are largely derived from selective weathering of biotite-plagioclase schist in the valleys and more resistant veined gneiss at higher altitudes. Further inland, the meta-sediments are gradually replaced by 1.74-1.82 Ga old granite and granodiorite, which also occur as intrusions in the KCS along with minor intrusions of mafic rocks.

The Quaternary deposits are strongly influenced by the latest glaciation. Drumlins and crag-and-tails are aligned in a SSW direction as the inland ice was moving from NNW. The ice retreated ca. 10,200 a BP

(Stroeven et al., 2016), leaving up to 30 m thick till in sheltered areas, but also bare bedrock in more exposed locations. In addition, the large Vindel River Esker passes through the lower parts of the KCS adding large deposits of glaciofluvial material (Fig. 1c). The Quaternary deposits are predominately of local origin, displaying a silicate-dominated chemistry with quartz>plagioclase>K feldspar>amphiboles as the main minerals (Lampa et al., 2020). In areas with low topographic relief, peat has built up generally forming oligotrophic minerogenic mires. At the termination of the deglaciation, approximately half of the KCS was located below the highest postglacial coastline (situated at ca 257 m above present sea level). This has resulted in locally >60 m deep sand and silt sediments that now cover the lower parts of the KCS, deposited by the Vindel River during the course of the isostatic rebound.

Long-term environmental trends

The boreal region encompassing the KCS has experienced some strong environmental trends during the last several decades. Changes in climate, land-use, and long-range transport of air pollutants all have had a role to play in explaining some of these decadal changes. Despite having a highly developed research infrastructure in place, the co-occurrence, interaction, and synchronicity of several human interventions complicate our efforts to disentangle the cause-and-effects responsible for all changes that can be observed. However, by combining long-time series, large-scale experiments, and modeling we are now beginning to understand the role climate change, land-use, and atmospheric pollution have had in the past and present, and predict which roles they will have in the future.

Here we highlight some of the major trends in forest biomass growth, lake ice extent, catchment hydrology, and water quality for the KCS (Fig. 3). While some of the trends can be directly related to changes in climate, such as the increasingly earlier lake ice-out, other trends are more likely related to atmospheric pollution, namely, the decline in stream calcium that relates to the recovery from acid deposition. Increased forest biomass production, stream water brownification, and increase in ET are likely caused by a combination of interacting factors. Such interactions, and the fact that some catchments respond while adjacent systems do not, call for the need of continued research to disentangle these cause-and-effect mechanisms. In addition, we urgently need to provide predictions for what these large-scale environmental changes will mean for northern environments. These include the direct and indirect effects on carbon and greenhouse gas (GHG) balances, atmospheric radiative forcing, terrestrial and aquatic biodiversity and water quality, but also for the industry and livelihood of communities in northern regions. Living up to these goals in an environment that is constantly changing, requires maintaining research infrastructures that take a landscape scale perspective and include the most important processes in the atmosphere, vegetation, soils, bedrock, and water, as well as the interactions between them.

Research infrastructure (max 2500 words)

The ambition of KCS is to take a holistic ecosystem perspective of the boreal landscape to understand, elucidate, and predict the role of internal and external drivers of catchment processes across a range of scales. In our approach, we combine state-of-the-art technology to capture various ecosystem processes with traditional research tools and basic environmental monitoring. This includes processes and dynamics of living and non-living ecosystem compartments, as well as the fluxes of energy, water, carbon, nutrients, metals, and other compounds within and between the atmosphere, lithosphere, cryosphere, and hydrosphere. In the KCS, we do this by combining a large, central, research facility – namely, the ICOS research tower – with supplemental infrastructures distributed across the entire landscape (Fig. 4). In addition to these facilities, the KCS also offers a number of large scale and/or long-term experimental facilities. Below we outline some of the most central of these facilities and data.

Surface water program

The hydrology and water chemistry program has been a central feature of the KCS program since the beginning. The 50 ha C7 catchment (also called Svartberget or Nyänget in earlier work) is located in the central part of the research station and was established in 1980 and marks the start of what today is the

KCS. Since 1984, the two sub-catchments that feed C7 have also been monitored, one completely forested (Västrabäcken, C2) and the other dominated by a mire (Kalkkälsmyren, C4). In 2002, the KCS expanded further and now includes 10 nested sub-catchments that are continuously monitored in the 6790 ha Krycklan catchment (including C2, C4 and C7; see Fig. 1 and Table 1). Heated huts allow year around measurements at C7 since 1982, at C2 and C4 since 2011, at C5 (a lake outlet) since 2012, and at C13 since 2014. The details of the hydrological monitoring program was presented by Karlsen et al. (2016a, b), while additional with-in lake measurements are being conducted in Stortjärn (Denfeld et al. 2020).

In total, ~12,000 stream water samples have been collected and analyzed from KCS stream sites. Regular sampling began at C7 in 1985, at C2 and C4 in 1990, and at most of the remaining sites in 2003 (Table 1). Most samples have been analyzed for basic chemistry (pH, major cat- and anions), dissolved and/or total organic carbon (DOC and/or TOC). Absorbance spectra (from 190 to 1100 nm) and dissolved inorganic carbon (DIC) have been part of the standard protocol since 2003. On selected samples, analysis of a suite of stable and radioactive isotopes (^{18}O , D, ^{14}C , ^{13}C , ^{15}N , $^{54/56}\text{Fe}$, $^{206/207/208}\text{Pb}$, ^{226}Ra , ^{230}Th , $^{234/238}\text{U}$), trace elements (including Hg, Pb, Rare Earth Elements (REE)) and persistent organic pollutants (PCBs, HCB and other) have also been included (see Laudon et al. 2011; Lidman et al. 2014; Josefsson et al. 2016; Tiwari et al. 2017; Ingri et al. 2018).

In addition to the regular sampling program a number of high-frequency, real-time measurements are now being conducted, especially in the central KCS area including streams C2, C4, C5, C6 and C7 (Fig 1d) using carbon dioxide (CO_2) and dissolved oxygen sensors, and measurements of absorbance spectra (Lupon et al. 2019, Riml et al., 2019; Gomez-Gener et al. 2020). The purpose of these is to capture rates of aquatic metabolism in relation to terrestrial contributions, but also to better understand the rapid, dynamic and non-linear stream biogeochemical responses to weather and climatic events that cannot be captured by the relatively infrequent sampling program.

Climate data program

As part of a reference monitoring program, above- and belowground climate data have been monitored since 1980 at the Svartberget station following World Metrological Organization (WMO) protocols. In total, approximately 100 meteorological variables are automatically monitored. Another twenty variables are manually observed, including phenological observations.

Precipitation as both rain and snow have been measured as part of the reference climate monitoring program at Svartberget field station since 1980. Rain and snow chemistry have been sampled since 1983, with each precipitation event collected and stored as individual samples, bulked monthly, and analyzed for chemistry. Snow accumulation and snow density measurements have been monitored approximately weekly since 1980 (Laudon and Löfvenius, 2016).

Soil water program

Soil water from three soil profiles (called the S-transect) located 4, 12 and 22 m from the C2 stream have been monitored 5-12 times per year since 1995 for water isotopes and water chemistry (Nyberg et al. 2001; Bishop et al., 2004; Lidman et al. 2017, Blackburn et al. 2017). The S-transect is aligned based on topography, following the lateral flowpath of groundwater. Each profile consists of measurements at six soil depths between 5 and 90 cm using ceramic suction lysimeters (P100). Soil water content using Time-domain reflectometry (TDR) and soil temperatures are measured at the same depths. A similar setup was installed in one of the wetland soils upstream of C4 to monitor soil water chemistry since 1997 using 12 nested wells extending to different depths, ranging from 25 to 350 cm below the ground surface (Lidman et al. 2013; Sponseller et al. 2018).). In 2007, the Riparian Observatory of Krycklan, a complementary set of transects to represent a range of topographic situations was also established (Grabs et al., 2012).

Ten pairs of DRIP (Discrete Riparian Inflow Point) and non-DRIP well transects were established in 2015 in riparian zones in central KCS streams (Fig. 1d). Each pair is located adjacent to each other and therefore experience comparable environmental conditions, except for in the groundwater hydrology. DRIP sites are

located on the receiving end of converging groundwater flow paths, and are characterized by shallow water tables, often reaching the soil surface before converging with streams (see Leach et al. 2017). Non-DRIP sites are situated in more elevated, drier riparian areas. Each transect is equipped with three fully screened groundwater wells, situated in riparian (0-3 m distance from the stream), transition (10 m distance from the stream), and upland (20 m distance from the stream) areas (Ploum et al. 2020).

Groundwater program

Monitoring of the groundwater (>2 m) in the KCS has been conducted since 1980 by the Swedish Geological Survey (SGU) as part of their national monitoring. The past decade has seen a continuous expansion of the groundwater well network, currently resulting in over 150 wells within the KCS. With the exception of a 150 m deep well penetrating the bedrock, the wells are placed in the Quaternary deposits at depths between ca. 2-30 m. Most wells are of piezometer type, to allow the determination of the hydraulic head in given soil layers as well as extraction of groundwater samples for chemical and isotopic analyses at specific depths. The wells are primarily distributed in the central parts of the catchments, but there are also well-clusters where the groundwater from different depths at the same location can be investigated (Fig 1d). The purpose of these installations has been to enhance the understanding of deeper groundwater in the landscape, with respect to transit times (Peralta-Tapia et al. 2015), flow pathways (Lidman et al. 2016), residence times (Kolbe et al., 2020) and water chemistry (Klaminder et al. 2011). On-going collaboration with the SGU is aimed at developing a 3D soil map for the entire KCS in order to provide a stronger foundation for further exploration of the links between Quaternary deposits, hydrology, and water quality. The project includes further geophysical investigations of the area, including transient electromagnetics, drilling, and installation of more groundwater wells.

Biosphere-atmosphere exchanges of carbon, water and energy

A combined Integrated ICOS atmosphere-ecosystem station is located in the center of KCS (Fig 1). ICOS is a pan-European research infrastructure with the mission to produce standardized, high-precision, and long-term observations of greenhouse gases and to facilitate research to understand the carbon cycle (www.icos-cp.eu/). The ICOS Svartberget infrastructure has been in operation since 2014 within ICOS Sweden. The atmosphere and ecosystem stations were officially labelled and designated as ICOS Europe stations in 2017 and 2019, respectively. All data collected are quality controlled by central thematic centers and made openly available via the ICOS Carbon Portal (<https://data.icos-cp.eu/portal>).

The atmosphere station conducts measurements of concentrations of CO₂, carbon monoxide (CO), methane (CH₄), as well as air temperature and humidity at three levels (35, 85, 150 m height). At 150 m, concentrations of ¹⁴CO₂ and ¹³CO₂ are also measured with lower time resolution (i.e. by periodic flask sampling). The atmospheric concentration measurements have a footprint of several hundred kilometers and in combination with other atmospheric measurement stations in Northern Europe capture subcontinental scale conditions.

The ecosystem station provides measurements of CO₂, water (i.e. evapotranspiration), and energy fluxes using the eddy covariance (EC) technique. These measurements (conducted at 34.5 m height) have a footprint of several hundred meters representing the specific ecosystem conditions in the vicinity of the tower, including catchments C2 and C7. In addition, key meteorological (i.e. radiation, temperature, wind, humidity, precipitation) and soil environmental (temperature, moisture, heat flux and water table level) variables are continuously monitored on the tower and along four soil depth profiles, respectively. Permanent sample plots for inventories of tree and understory vegetation biomass, species, leaf area, phenology and leaf chemistry, as well as litter fall give additional information on the biotic ecosystem properties.

The ICOS infrastructure also serves as a platform for establishing and connecting external research projects. For instance, the installation of two more EC systems at 60 and 85m height along the ICOS tower provides additional estimates of CO₂, CH₄, water and energy exchanges at the landscape scale (i.e. few km radius), roughly spanning the area of the KCS (Chi et al., 2019). Integration of these landscape EC measurements with aquatic fluxes of carbon species via stream runoff has resulted in a first estimate of the net landscape carbon balance (NLCB) for the KCS (Chi et al., 2020). In addition, the combination of EC and sapflow

measurements around the ICOS tower has provided an opportunity to partition the forest water cycle components (Kozii et al., 2020). Furthermore, the concentration measurement profile including several levels along the 150 m tall tower has enabled investigations of atmospheric organic pollutants (Bidleman et al. 2017), as well as water isotope and mercury dynamics. The ICOS tower structure also hosts multispectral sensors, phenology cameras and UAVs within the SITES-Spectral infrastructure to collect spectral data for estimating ecosystem vegetation properties at various spatial and temporal scales.

Sapflow measurements

In spring 2016, a network of Granier sap flow sensors (Granier 1985) was installed in 70 trees (30 *Pinus sylvestris*, 30 *Picea abies* and 10 *Betula sp.*) to continuously measure tree-level transpiration, an integrated measure of whole tree hydraulic stress, in the three tree species that are dominant in Fennoscandian boreal forests. This technique includes a pair of thermocouple sensors that detect changes in the temperature difference ($[?]T$) from the baseline ($[?]T_m$ at zero flow), which in turn reflects the flow rate of water through stems (Granier 1987). In addition, a field deployed Picarro L2131-i analyzer provides continuous, high temporal resolution isotopic measurements of tree xylem water. Taken together, these measurements provide a unique opportunity to test how changes in environmental conditions affects stand evaporation and tree-level transpiration across a range of temporal scales as well as directly compare the importance of transformations into other water balance components (*i.e.*, streamflow) within a northern boreal headwater catchment.

Terrestrial and stream biology

Repeated forest and below canopy surveys of 550 permanent 10-m radius plots have been conducted 2016 and 2020. By linking these surveys with concurrent Lidar scans and soil inventory, the ambition is to develop a mechanistic link between forest growth, soil conditions, and modeled groundwater pathways. A systematic survey of riparian plant communities was conducted in 2013, depicting the relationship between vascular and non-vascular plant diversity with stream size and groundwater flow paths including 32 KCS sites (Kuglerova et al. 2014, Kuglerova et al. 2015).

Macroinvertebrate and stream microbial data have been collected repeatedly from number of streams within the catchment and used in different contexts (e.g., Gothe et al. 2013, Jonsson et al. 2017, Burrows et al. 2017). Survival experiments on fish (Serrano et al. 2008) and invertebrate population studies (Petrin et al. 2007) have been conducted in several of the monitored streams. In addition, the main stem of the Krycklan river network has been used as an unimpacted (by timber floating) reference site in a number of studies of stream hydrogeomorphology (Polvi et al. 2014), riparian plant diversity and composition (Hasselquist et al. 2015), riparian nutrient cycling (Hasselquist et al. 2017), instream ecosystem functioning (Frainer et al. 2018), and biodiversity (Hasselquist et al. 2018). Since 2007, C7 is also a part of national freshwater monitoring program under which aquatic macroinvertebrates are annually collected to depict long-term biodiversity trends.

Lidar data

In addition to the national lidar scans (2008-2015, point density 0.5 points m^{-2} and 2019-2025, point density 1-2 points m^{-2}), KCS has been scanned during different campaigns, allowing for high resolution DEMs down to 0.5 m resolution and providing detailed tree level data. The first specific scanning was conducted in 2006 with a point density of up to 10 points m^{-2} . In 2008, the KCS was scanned as part of the BIOSAR campaign with the TopEye system S/N 425 mounted on a helicopter, at a flight altitude of 500 m above ground level for main strips and 250 m above ground level for cross strips, using an average point density of approximately 5 points m^{-2} in the main strips and 15 points m^{-2} in the cross strips. In 2015, the KCS was scanned by Terratec with the Optech Titan X sensor at a flight height around 1000 m giving a point density of on average 20 points m^{-2} . This sensor scanned at 3 wavelengths, 532 nm (green), 1064 (NIR), 1550 nm (SWIR). In 2019, the KCS was scanned with Riegl VQ-1560i-DW 532 nm (green) and 1064 (NIR) with an average point density of 20 points m^{-2} .

Experimental platforms

Unraveling how the climate, land-use and other environmental perturbations can affect short and long-term patterns in hydrology, water quality and biodiversity, requires more than just good empirical data from the past and present. It will be equally important to generate data from controlled conditions outside the natural range of variability previously experienced, mimicking anticipated external forcings in the future. Experimental manipulations in the field are of fundamental importance in this respect, as they can mimic expected extreme conditions and responses to future perturbations. This is needed to enhance our mechanistic understanding and constrain model predictions. The already existing infrastructure and large availability of land for research at the KCS makes large-scale and long-term experiments conceivable and relatively simple to conduct.

The Trollberget Experimental Area (TEA) was established in 2018 to test best practices for management of the historical ditch-network and develop new methods to mitigate negative effects on freshwater environments. The ~ 60 ha site is located 1 km from the KCS and drains into the Krycklan River just downstream of C16. It uses a replicated, catchment-scale approach to study four different research questions concerning forest water management, of which three are assessing the future of historic drainage ditches and one testing different riparian forest buffer designs. Given the relevance of the topic and the robustness of the experimental set-up a large set of researchers and projects are now involved in this satellite site.

Artificial drainage of peatlands through ditches have dewatered millions of hectares of northern peatlands for forestry. Recent estimates suggest that up to 1 million km of wetland ditches in Sweden alone have been created (Agren and Lidberg 2019), many of which are now not functioning (Hasselquist et al. 2019). The future fate of these drainage ditches can be to: 1) clean them to ensure resumed drainage, 2) ecologically restore them to a more natural state, or 3) leave them unmanaged. At TEA, we have created a side-by-side comparison of these three different management options with the objective of determining their effects on water quality and quantity as well as their role in altering the land-atmosphere greenhouse gas balance. Specifically, we have the goal of quantifying the impact of peatland forest harvest, ditch cleaning, and filling-in of ditches (ecological restoration) on dissolved organic matter export and quality, greenhouse gas exchanges, nutrient and sediment export, export and speciation of mercury, as well as water storage. Here we take a catchment-scale approach for monitoring dynamics and export from our different treatments; six experimental catchments with an average size of 10 ha are being monitored in TEA, where four catchments in the nearby KCS sites serve as controls.

In addition, TEA includes a riparian buffer experiment with the goal to directly compare the functioning of narrow (5 m) to wider (15 m) buffers. Monitoring of nutrient export, sediments, riparian vegetation, and greenhouse gas fluxes in the stream and riparian zone are being conducted. The unique opportunity of comparing before and after treatment as well as the differences in responses to buffer widths, will allow for more informed management decisions in the future.

A lake –stream experimental facility in the central part of KCS (Fig 1d) allows for controlled flooding/drought manipulations in a 110 ha catchment system. A water regulating facility at outlet of the lake, just upstream of the sampling site C5, can be used to flood the lake and dry out the 1400 m stream reach to the downstream sampling site at C6 (Gomez et al. 2020), or alternatively to use the water reservoir in the lake to test flooding conditions downstream (Leach and Laudon, 2019).

Soil frost experiment: The KCS supports the longest (>17 years) ongoing soil frost manipulations experiment in the world (Campbell and Laudon, 2019), contributing with knowledge critical for interpreting how changes in winter conditions will affect soils and streams. The ongoing experiment has for example been used to study the effects DOC (Haei et al. 2012), CO₂ emissions (Oquist and Laudon, 2008), decomposition processes (Kreyling et al. 2013) and root distribution (Blume-Werry et al. 2016).

Lake mesocosms and experimental flumes: Although observational studies have tremendously advanced our understanding of freshwater systems, their disadvantages are that many parameters typically correlate and that causality seldom can be determined with any certainty (Downes, 2010). Therefore, ex-

perimental facilities are useful to disentangle the effects of individual parameters or their combinations, especially in situations of unimodal responses. In lake Stortjärn, a floating experimental platform consisting of 16 cylindrical 700 L enclosures submerged in the lake can be used to perform controlled in-site experiments (Cordero et al. 2021). Experiments can be performed concurrently on 5 lakes across Sweden as part of the SITES-AquaNet infrastructure (<https://www.fieldsites.se>).

A set of 12 outdoor, experimental flumes (i.e. channels) were built in 2020 within the KCS and fed by water from an adjacent stream. Each channel is 20 cm wide, 20 cm deep, and 15 m long. Water is pumped into one collector tank and then distributed through four manipulation boxes, allowing four different concurrent treatments with three replicates each. The slope and flow of each channel is adjustable ranging from 0 - 1.5 degrees for slope and 0 - 1 L s⁻¹ for flow. The channels can also be experimentally heated using warming cables. The bottom substrate in each channel is composed of local, natural gravel and pebbles but can also be manipulated.

In addition to the water and soil experiments, over 50 long-term forestry and biodiversity experiments are conducted within the KCS area. The oldest of these still in use began in 1911 to test the effect of different provenance of seedlings at this latitude, in order to better understand plant survival and wood quality. Other experiments include fertilization effects on leaf traits of understory shrubs (Palmroth et al. 2014), the effect of biochar addition on plant communities (Gundale et al. 2016), and thinning and fertilization effects on Scots pine (Valinger et al. 2019).

Database and sample archive

The guiding principles of the KCS research infrastructure are open data, data sharing, and always welcoming new researchers and field studies. The Svartberget research station, run by the Swedish University of Agricultural Sciences Faculty of Forestry offers full access to 2500 ha of land within the KCS for new field studies, and close collaboration with land-owners in the area allows for the establishment of new sampling programs and large scale experiments.

For every water sample ever collected within the KCS research program, duplicate samples have been stored at -18° C in acid-washed bottles for chemical analysis, and at +4°C, in glass bottles for water isotopes. All in all, the Krycklan archive contains over 25,000 unique samples. Additionally, the KCS database contains more than 15 million datapoints on water chemistry, and even more data from long-term high-resolution timeseries on physical parameters. The KCS database builds on a concept we call FAIR & Square (Laudon and Taberman, 2016), which is guided by Data FAIR port requirements (<https://www.datafairport.org/>). While FAIR stands for Findable, Accessible, Interoperable, and Reusable, ‘Square’ symbolizes the importance of acknowledging of the original data producer. An important aspect of FAIR & Square is that we try to provide clear, precise and standardized metadata that can answer questions about “when, where, how, and why” samples have been collected, analyzed and quality controlled.

An important principle in the FAIR & Square concept is to acknowledge the effort that has gone into acquiring the data being shared. In short we ask users to: 1) Always cite the original source of data used, 2) acknowledge other studies that touch on similar aspects that your work builds on, 3) do not distribute data to third parties in order to allow updates/corrections and to avoid spreading erroneous data, and 4) recognize the original data producer properly in acknowledgments if they provided data, or by offering co-authorship if they contributed with significant work, important ideas, and/or helped with essential interpretation.

5.0 Directions for the future

At a time when our environment is under increasing pressure from global change it is alarming that many leading field research infrastructures are under increasing threat to be down-sized or even closed. Failure to recognize recognize and prioritize the value of long term research and monitoring compromises the possibilities that science can contribute to long-lasting solutions. Never before has the need been greater to continue the collection of empirical data that together with past data can provide baseline conditions before

climate change obscures the clues to how ecosystems functioned without this massive human influence . Understanding the fate of surface and groundwater resources, carbon exchange processes, and threats to biomass production are questions of fundamental importance for the future. Instead, the trend in monitoring is going the other way, where empirical studies are declining relative to modeling-based analysis. While modeling will be an important part of environmental science, models must be constrained, tested, and validated by empirical field data to be useful. To cite Sherlock Holmes by Sir Arthur Conan Doyle, ‘It is a capital mistake to theorize before one has data. Insensibly one begins to twist facts to suit theories, instead of theories to suit facts.’

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Table 1. Catchment characteristic of streams included in the KSC stream sampling program, Black numbers denote continuously monitored streams grey numbers denote project activated stream sampel collection.

¹ Calculated from the property map (1:12,500, Lantmäteriet Gävle, Sweden).

² Calculated from the quaternary deposits map (1:100,000, Geological Survey of Sweden, Uppsala, Sweden). Peat was excluded from the table because it corresponds closely to the mire coverage from the property map.

³ Determined for the entire catchment using correlations between a forest inventory (110 plots) and LiDAR measurements.

⁴ Tree species distribution determined from IR-orthophotos for 1751 stands.

Catchment	Area	Lakes ¹	Forest ¹	Open land ¹	Arable land ¹	Mire ¹	Till ²	Thin soils ²	Rock outcrops ²	Sorted
	(ha)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)
C1	48	0,0	98	0,0	0,0	2,0	92,1	7,9	0,0	0,0
C2	12	0,0	100	0,0	0,0	0,0	84,2	15,7	0,0	0,0
C3	4	0,0	59	0,4	0,0	40,4	43,2	0,0	0,0	3,7
C4	18	0,0	56	0,0	0,0	44,1	22,0	27,0	0,0	0,0
C5	65	6,4	54	0,0	0,0	39,5	40,4	5,5	0,0	0,0
C6	110	3,8	71	0,0	0,0	24,8	53,7	11,3	2,5	0,0
C7	47	0,0	82	0,0	0,0	18,0	65,2	15,4	0,0	0,0
C8	230	0,0	88	0,0	0,0	11,9	62,8	18,6	1,7	0,0
C9	288	1,5	84	0,0	0,0	14,1	69,1	6,8	1,7	4,1
C10	336	0,0	74	0,0	0,0	26,1	59,9	10,8	0,0	0,5
C12	544	0,0	83	0,0	0,0	17,3	66,6	8,4	0,0	5,9
C13	700	0,7	88	0,2	0,6	10,3	60,9	8,9	1,3	15,9
C14	1410	0,7	90	0,9	2,9	5,4	44,9	8,1	1,6	38,1
C15	1913	2,4	82	1,4	0,1	14,5	64,8	8,1	0,7	9,5
C16	6790	1,0	87	1,1	1,9	8,7	50,8	7,4	1,2	30,2
C20	145	0,0	88	0,0	2,6	9,6	45,0	20,3	1,8	21,4
C21	26	0,0	99	0,0	0,0	1,0	52,8	3,4	0,0	43,8
C22	491	2,6	68	0,0	0,0	29,0	61,2	7,2	0,6	0,0

Table 2. Catchment characteristics of the Trollberget Experimental Area (TEA)

Catchment	Area	Peat	Till	Rock outcrops	Ditch length	Ditch density	Type of management	Length of ditches
	(ha)	(%)	(%)	(%)	(m)	(m/ha)		(m)
DC1	6,7	0	100	0	849	126	Cleaned	658
DC2	4,4	0	100	0	1117	252	Left alone	0
DC3	8,4	0	100	0	1780	212	Cleaned	1077
DC4	10,7	34	63	2	795	72	Left alone	0
R1-	47	28	43	18	1986	42	Restored	677
R2	60	23	56	22	5189	86	Restored	824

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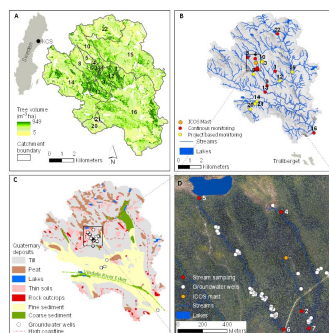


Figure 1. The Krycklan Catchment Study shown with sub-catchment areas and corresponding tree density (panel a), the stream network, including the Trollberget Experimental Area in the south (panel b), the distribution of quaternary deposits (panel c), and a close up on the central area, which included sub-catchments C2, C4, C5, C6, and C7, the experimental stream segment (between C5 and C6), and approximately 100 groundwater wells (panel d).

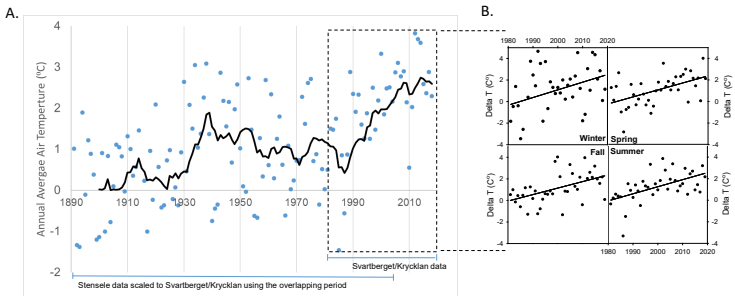


Fig 2. panel A. Mean annual air temperature at the Svartberget from 1890-present with 10-year running average (solid line). Data prior to 1980 are modeled from the scaling relationship with a nearby climate station at Stensele (150 km to northeast). The 24 year overlap (1980-2004) in the air temperature records at these two stations yielded a linear correlation with slope = 1.041, intercept = - 0.008, $r^2 = 0.93$, $p < 0.001$, and RMSE = 2.786. Panel B shows the seasonal trends in air temperature from the Svartberget station from 1980 to present.

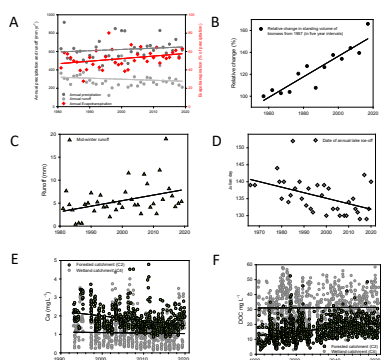


Figure 3. Examples changing hydrological and chemical conditions in the Kryckian Catchment Study over the last 30-60 years. These changes include an increase in evapotranspiration (ET, trend: $+0.3\% \text{ yr}^{-1}$) at the C7 catchment measured as the difference between precipitation and discharge (**panel A**). Long-term increases in forest biomass in the extended Kryckian area relative to estimates in 1957 (trend: $+1.0\% \text{ yr}^{-1}$; **panel B**; Swedish National Forest Inventory, SLU, unpublished data). An increase in mid-winter (March) runoff in the C7 catchment (trend: $+0.1 \text{ L s}^{-1} \text{ yr}^{-1}$; **panel C**). Declines in the timing (date) of lake ice-off in the spring, based on a 55-year record collected 25 km north of the Kryckian (trend: $-0.2 \text{ days yr}^{-1}$; Rune Axelsson, unpublished data; **panel D**). Declining Ca concentrations in a forest-dominated stream (C2; trend: $-0.02 \text{ mg L}^{-1} \text{ yr}^{-1}$), but not for an adjacent mire-dominated stream (C4; **panel E**). Increasing DOC concentrations in same forested stream (C2; trend: $+0.2 \text{ mg L}^{-1} \text{ yr}^{-1}$), but not in the mire-dominated counterpart (C4; no trend, **panel F**). All trends were calculated using Mann Kendall tests.

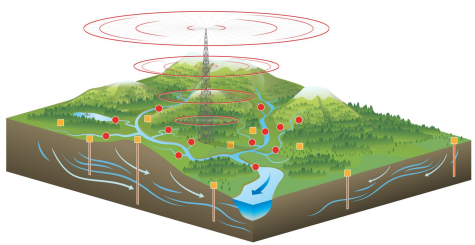


Figure 4. Schematic depiction of the major field installations in the KCS, including the stream and groundwater monitoring network, as well as the 150 m ICOS tower in the catchment center.

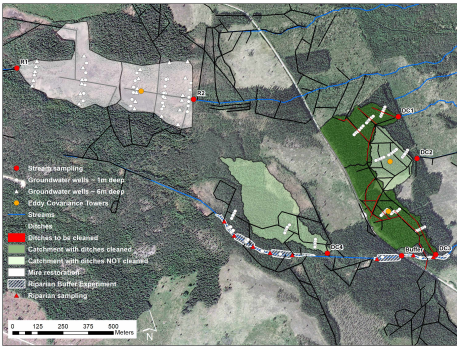


Figure 5. The Trollberget Experiment Area (TEA) used to study the effect of wetland restoration, ditch network maintenance and riparian buffer design.