The Krycklan Catchment Study—A flagship infrastructure for hydrology, biogeochemistry, and climate research in the boreal landscape

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[1] The Krycklan Catchment Study (KCS) provides a unique field infrastructure for hillslope to landscape-scale research on short- and long-term ecosystem dynamics in boreal landscapes. The site is designed for process-based research assessing the role of external drivers including forest management, climate change, and long-range pollutant transport on forests, mires, soils, streams, lakes, and groundwater. The overarching 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 environmental data, and (3) support the development of models and guidelines for research, policy, and management.

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1. Introduction

[2] The boreal region encompasses a large part of the world's forests and stores approximately one third of the global terrestrial carbon pool. With the anticipated climate change, environmental conditions in the boreal region are predicted to move toward a new state. This will potentially have unforeseeable consequences for fundamental aspects of ecosystem functioning, including water balances, biogeochemical cycling, and ecology in northern regions, that are presently defined by long, cold, and snow-rich winters.

[3] Despite its potential vulnerability, large geographic extent and growing economic significance; the boreal region has been subject to comparatively limited long-term, cross-scale, experimental, process-based, and integrative research. One important reason for this has been the limitation of well-established, easily accessible, and high-quality research infrastructures that encompass all major components of the boreal landscape, including forests, soils, mires, and surface waters. An extraordinary exception to this is the Krycklan Catchment Study (KCS) that has provided a unique opportunity for integrated process-based research in the boreal region for decades.

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[4] The KCS is quite possibly unique in the boreal ecozone for the range of spatial scales at which data are collected. The instrumented hillslopes and network of riparian lysimeters provide process-based insights into terrestrial controls on surface water quality across a range of spatial scales. Nested catchment studies are needed to gain insight in the spatial scale at which environmental stressors such as climate change or acidification are manifested in the forest landscape [*Soulsby et al*., 2006]. While there are a number of well-monitored headwater catchments in the boreal region [i.e., *Löfgren et al*., 2011; *Petrone et al*., 2006] there are only a few other long-term, well supported snow melt-dominated nested research catchments across the world [see *Tetzlaff et al*., 2013].

[5] Forest research in the Krycklan catchment started 100 years ago when the Svartberget and Kulbäcksliden experimental forests were established. Some early studies were related to forest paludification [*Malmström and Tamm*, 1926] and thinning effects on soil frost [*Ångström*, 1936]. When the new Svartberget field station, in the center of the Krycklan catchment, was created in the late 1970s, the water research focus was on forest hydrology and biogeochemical cycling [*Grip and Bishop*, 1990]. This early work was followed in the 1990s by a decade of more intensive work on the role of acid deposition [*Bishop*, 1991] that resulted in a paradigm shift in understanding the difference between anthropogenic acidification and natural acidity in dissolved organic carbon (DOC)-rich boreal waters [*Erlandsson et al*., 2011]. A few recent examples of the close to 500 peer-reviewed papers in the catchment includes studies on metals [*Björkvald et al*., 2008], weathering [*Klaminder et al*., 2011] persistent organic pollutants [*Bergknut et al*., 2010], carbon cycling [*Wallin et al*., 2013], hydrology [*Lyon et al*., 2012] and base cation cycling [*Ledesma et al*., 2013].

The recent work on DOC trends shows increasing concentrations over the last decade [*Oni et al*., 2013] similar to other regions in Sweden [*Erlandsson et al*., 2008] and Europe [*Monteith et al*., 2007].

[6] Recognition of the need for process-based research at the landscape scale when addressing the influence of climate on aquatic ecology resulted in an expansion of focus from the 50 ha Svartberget catchment to the 6790 ha Krycklan catchment in 2002 [*Laudon et al*., 2011]. This led to a broadening of both the fundamental research questions and the management issues addressed. In recent years, KCS has transformed into an experimental platform for testing basic [*Ågren et al*., 2012] and applied research [*Öhman et al*., 2009] questions in natural environments. The platform is continuously attracting new scientific projects, but has also been the subject of considerable large interest from industry and environmental authorities.

[7] The main objective of KCS is to provide a state-of-the-art field research infrastructure that includes all aspects of the boreal landscape; forests, mires, soils, lakes, streams, and groundwater. In 2013, over 50 scientific projects involving scientists from over 20 counties were conducting research at KCS. To maximize the applicability of the infrastructure and existing data, one important route forward is to stimulate and facilitate international comparisons, collaborations, and syntheses. As a step in this direction, we are now making an effort to make the field infrastructure more visible for potential users at the same time as we make much of the collected and analyzed field data accessible (www.slu.se/krycklan).

2. Site Description

[8] KCS is located approximately 50 km northwest of the city of Umeå in northern Sweden (64°, 14′N, 19°46′E). The Svartberget subcatchment (Nyänget or catchment 7 (C7)) located in the upper parts of the Krycklan catchment was established as a research catchment 1980. Since 1984, forest (Västrabäcken, C2) and mire-dominated (Kallkälsmyren, C4) subcatchments of Svartberget have been monitored. In 2002, the research at the 50 ha Svartberget catchment expanded and now includes 18 partly nested subcatchments in the 6790 ha Krycklan catchment (including C2, C4, and C7; see Figure 1 and Table 1).

[9] Bedrock in the Krycklan area is dominated by Svecofennian metasediments/metagraywacke (94%) with 4% acid and intermediate metavolcanic rocks and 3% basic metavolcanic rocks. Quaternary deposits are dominated by till (51%) and sorted sediments (30%). The catchment ranges in elevation from 114 to 405 m above sea level (a.s.l.). The region was glaciated and is undergoing isostatic rebound following the last deglaciation. The highest

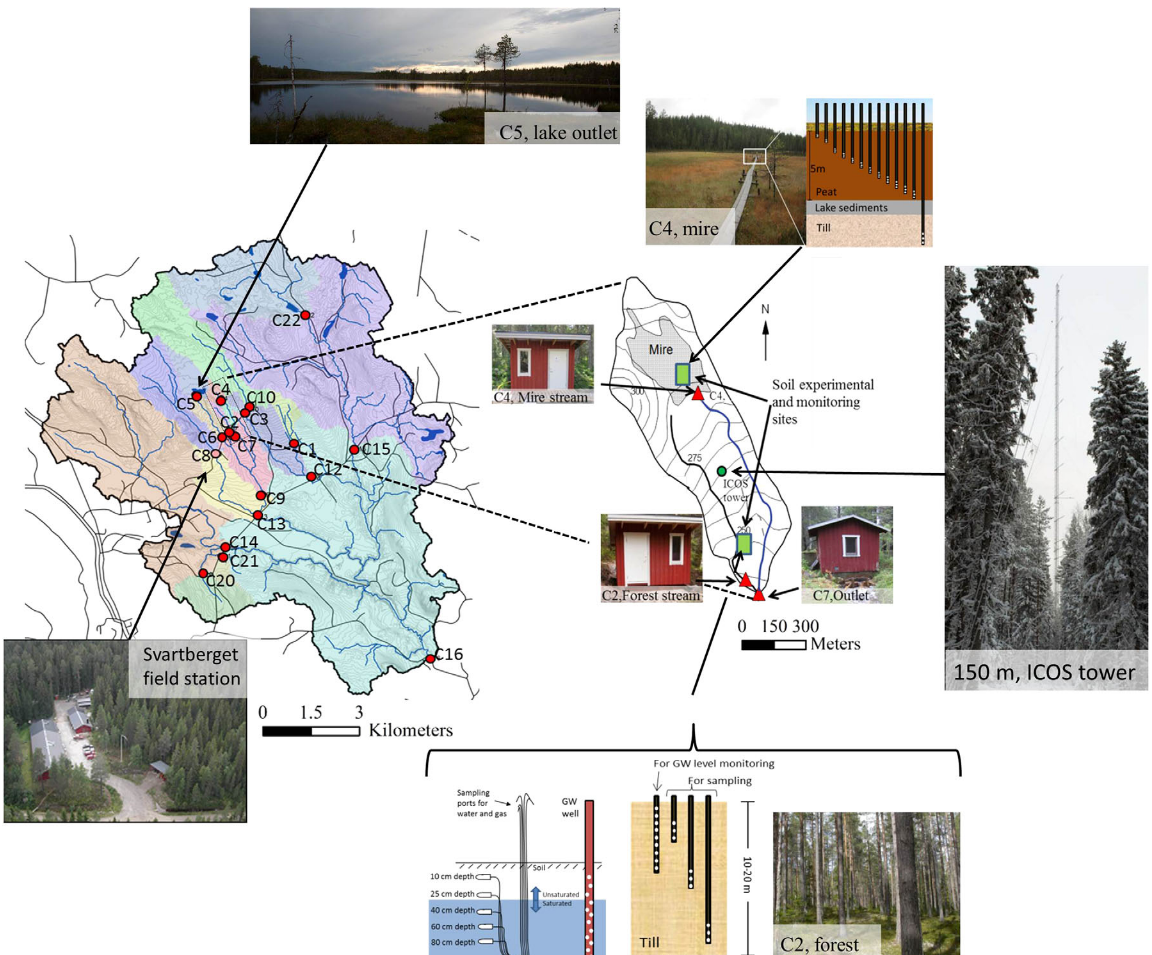

Figure 1. Major field installations in KCS.

Table 1. Catchment Characteristic of 18 Streams Included in This Study

Catchment	Area (ha)	Lakes[a] (%)	Forest[a] (%)	Open Land[a] (%)	Arable Land[a] (%)	Mire[a] (%)	Till[b] (%)	Thin Soils[b] (%)	Rock Outcrops[b] (%)	Sorted Sediment[b] (%)	Tree Volume[c] (m^3 ha^{-1})	Birch[d] (%)	Spruce[d] (%)	Pine[d] (%)	Stand Age[c] (years)
C1	48	0.0	98.0	0.0	0.0	2.0	92.1	7.9	0.0	0.0	187	2	63	35	87
C2	12	0.0	99.9	0.0	0.0	0.0	84.2	15.7	0.0	0.0	212	0	36	64	103
C3	4	0.0	59.0	0.4	0.0	40.4	43.2	0.0	0.0	3.7	133	1	5	93	77
C4	18	0.0	55.9	0.0	0.0	44.1	22.0	27.0	0.0	0.0	83	0	45	55	57
C5	65	6.4	54.0	0.0	0.0	39.5	40.4	5.5	0.0	0.0	64	12	26	62	50
C6	110	3.8	71.4	0.0	0.0	24.8	53.7	11.3	2.5	0.0	117	4	26	70	69
C7	47	0.0	82.0	0.0	0.0	18.0	65.2	15.4	0.0	0.0	167	1	35	64	86
C8	230	0.0	88.0	0.0	0.0	11.9	62.8	18.6	1.7	0.0	118	12	20	68	71
C9	288	1.5	84.4	0.0	0.0	14.1	69.1	6.8	1.7	4.1	150	6	29	65	78
C10	336	0.0	73.8	0.0	0.0	26.1	59.9	10.8	0.0	0.5	93	12	21	68	60
C12	544	0.0	82.6	0.0	0.0	17.3	66.6	8.4	0.0	5.9	129	8	34	57	72
C13	700	0.7	88.2	0.2	0.6	10.3	60.9	8.9	1.3	15.9	145	8	25	68	78
C14	1410	0.7	90.1	0.9	2.9	5.4	44.9	8.1	1.6	38.1	106	10	23	67	62
C15	1913	2.4	81.6	1.4	0.1	14.5	64.8	8.1	0.7	9.5	85	10	26	64	54
C16	6790	1.0	87.2	1.1	1.9	8.7	50.8	7.4	1.2	30.2	106	10	26	63	62
C20	145	0.0	87.7	0.0	2.6	9.6	45.0	20.3	1.8	21.4	59	16	16	68	42
C21	26	0.0	98.9	0.0	0.0	1.0	52.8	3.4	0.0	43.8	138	8	10	82	74
C22	491	2.6	68.3	0.0	0.0	29.0	61.2	7.2	0.6	0.0	78	10	22	67	54

[a]Calculated from the property map (1:12,500, Lantmäteriet Gävle, Sweden).
[b]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.
[c]Determined for the entire catchment using correlations between a forest inventory (110 plots) and LiDAR measurements.
[d]Tree species distribution determined from IR-ortophotos for 1751 stands.

postglacial coastline therefore traverses the catchment at approximately 257 m a.s.l dividing the catchment in two distinctly different areas. At higher altitudes the quaternary deposits are dominated by till and peat; at lower altitudes, postglacial sedimentary deposits dominate. In the till soils, well-developed iron podzols dominate the forest floor soils, but near the stream channels, the organic content increases, forming a riparian peat zone along the streams. Forest covers 87% of the catchment, mires 9%, and thin soils and rock outcrops 7% and 1%, respectively. The land use is dominated by forestry, approximately, 25% of the Krycklan catchment has been protected since 1922, but most of the other area is second growth forest. From satellite imagery, 76 clear cuts were detected in the catchment between the years 1999–2010, covering a total of 7% of the catchment. Other than that, human impact is low with only 2% arable land and a population in the catchment of less than 100 people.

[10] The forests are dominated by Scots pine (*Pinus sylvestris*) (63%) and Norway spruce (*Picea abies*) (26%) with an understory dominated by ericaceous shrubs, mostly bilberry (*Vaccinium myrtillus*) and cowberry (*Vaccinium vitis-idaea*) on moss mats of *Hylocomium splendens* and *Pleurozium schreberi*. Peatlands are dominated by *Sphagnum* species. These peatlands can be categorized as acid, oligotrophic, and minerogenic mires.

3. Infrastructure Description

[11] *Climate Data From Krycklan*. The climate is characterized as a cold temperate humid type with persistent snow cover during the winter season. The 30 year mean annual temperature (1981–2010) is 1.8°C, January −9.5°C, and July +14.7°C, mean annual precipitation is 614 mm, annual mean runoff is 311 mm, giving an annual average evapotranspiration of 303 mm. Above and below ground climate data have been monitored since 1980 as part of a reference monitoring program. Standard meteorological variables are monitored following World Meteorological Organization (WMO) recommendations and additional variables of particular research interest. In total, approximately 100 variables are automatically measured with a time resolution of 10 min or hourly collection. Another 20 variables, including phenological observations, are manually recorded.

[12] An important recent addition to this monitoring program is the establishment of new research infrastructure in the center of the Krycklan catchment area, which is part of the ICOS-Sweden network (Integrated Carbon Observation System, www.icos-sweden.se). This includes one 150 m tower (Figure 1) for gradient measurements for greenhouse gases and one forest ecosystem station for measuring exchange fluxes of carbon dioxide, water vapor, and energy together with a number of other ecosystem variables. The ICOS stations will be served by a set of European facilities, including analysis laboratory and a thematic center responsible for data collection and technology development.

[13] *Precipitation Data*. Since 1980, daily precipitation as both rain and snow have been measured as part of the reference climate monitoring program at Svartberget field station (Figure 1). Precipitation chemistry has since 1983 been bulked monthly and analyzed for standard chemistry and hydrological isotopes.

[14] *Hydrological Data*. The record of stream discharge from the 50 ha Svartberget catchment began in 1981 inside a heated hut (allowing year around runoff monitoring) with hourly resolution. Discharge monitoring of C2 and C4 began during the ice-free season in 1984, and in 2003, discharge measurements at the remaining 15 sites became part of this program. In 2011, heated huts were constructed at C2 and C4, and in 2012 at C5 (a lake outlet) (Figure 1).

[15] *Stream Chemistry Data*. In total over 12,000 stream water samples have been collected and analyzed at the 18 monitored stream sites. In 1985 the sampling began at C7, in 1986 in C2 and C4, and in 2002 in most of the remaining sites (Table 1). The large majority of the samples have been analyzed for basic chemistry (pH, major cations, and anions), dissolved and/or total organic carbon (DOC and/or TOC). Absorbance spectra (from 190 to 1100 nm) and dissolved inorganic carbon (DIC) has been part of the standard protocol since 2003. On selective sample analysis of a suite of stable and radioactive isotopes (^{18}O, D, ^{14}C, ^{13}C, ^{15}N, ^{34}S, $^{206/207/208}Pb$, ^{226}Ra, ^{230}Th, $^{234/238}U$), metals (including Hg, Pb, rare earth elements (REE)) and persistent organic pollutants (PCBs, HCB and other) have also been included [see *Bergknut et al*., 2010; *Laudon et al*. 2011].

[16] *Soil Water Data—Long-Term Measurements*. Soil water from three soil profiles (called the S-transect) located 4, 12, and 22 m from the C2 stream have been monitored monthly since 1996 for hydrology and water chemistry. The transect is aligned based on the topography, so as to follow the lateral groundwater flow paths toward the stream [*Seibert et al.,* 2009]. Each profile consists of measurements at six soil depths between 5 and 90 cm using ceramic suction lysimeters (P100). Soil water content and soil temperatures are measured at the same depths (Figure 1). A similar setup has been used 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 (Figure 1).

[17] *Soil Water Data—Riparian Observatory*. Given the critical role of the riparian ecotone in defining the connection between soils and water, a riparian observatory at Krycklan (ROK) was initiated in 2007 [*Grabs et al*., 2012]. At present, the ROK consists of 20 soil lysimeter nests with at least five soil depths from different soil types across Krycklan. Data from these lysimeters provide unique insights into spatially patterns of soil and stream water interaction.

[18] *Groundwater*. Deep groundwater has been monitored quarterly since 1989 using four groundwater wells extending to 5 m depth in the mineral soil. This was established by the Swedish Geological Survey but is being continued as part of the program to study the role of deep groundwater [*Klaminder et al*., 2011]. In 2012, a network of 16 groundwater wells distributed across the catchment was established. These wells are between 2 and 12 m deep.

[19] *Stream/Soil Water Data—Archived Samples*. For each stream/soil water sample analyzed, a duplicate sample has been collected, frozen, and stored at $-18°C$. The purpose of this archive is to allow researchers to go back in time and reanalyze a specific sample or time series of samples for elements that was not/or could not be analyzed at the time of collection. One example of this is a retrospective study on lead isotopes [*Klaminder et al*., 2006].

[20] *Topographic Data*. Light Detection and Ranging (LiDAR) measurements have been conducted across the entire Krycklan catchment with a resolution of 10–15 measurements per m^2 [*Laudon et al*. 2011]. These measurements provide both a digital elevation map with greater than 1 m resolution and a detailed forest inventory of the entire 6790 ha Krycklan catchment [*Neumann et al*. 2012].

[21] *Aquatic Ecology Data*. A systematic survey of fish distribution using electrofishing was conducted in 2006 at 50 different locations in the Krycklan stream network. Fish survival experiments [*Serrano et al*., 2008] and invertebrate population studies [*Petrin et al*., 2007] have also been carried out in 15 of the 18 monitored streams. Water column microbial community productivity and respiration have been monitored extensively at numerous streams and lakes throughout KCS [*Berggren et al*., 2007].

4. Data Availability

[22] A main objective of the KCS field infrastructure and database is to make it more available for use by scientists, research students, authorities, industry, and the public. From the KCS database, two levels of availability are provided: (i) all data that have been validated using a standardized QA/QC protocol are made publically available for downloading (www.slu.se/krycklan) and (ii) data that has not yet been fully validated can be made available upon request (Krycklan.database@slu.se) after contact with the responsible person to ensure the integrity and validity of the data. The publicly available data include the longest time series of hydrological and standard biogeochemical information as well as long-term temperature and precipitation data. Summary data on climate, runoff, and total loads of different constituents are also included as are maps, GIS files, photos, reports, and publications. Also, metadata describing all data holdings in the database are provided.

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