Forestry Impact on Water Quality: a Landscape Perspective on Dissolved Organic Carbon

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Cover: Spring freshet at the sampling site BA-2 in April 2009.
(photo: J. Schelker)

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Abstract

Dissolved organic carbon (DOC) is a fundamental variable defining boreal stream ecosystems. In this thesis the impact of forestry practices that are commonly performed in the boreal regions of Scandinavia for stream water quality were evaluated. The thesis is based on combining the use of primary data from the *Balsjö paired catchment experiment* in northern Sweden with various modeling approaches.

Final-felling strongly increased DOC concentrations in boreal first-order streams during the first four years after harvest. Median concentrations increased by 3.0 mg/L after clear-cutting and 6.2 mg/L after site preparation with concentrations being 5-24 mg/L higher in the clear-cut than in the reference catchment during summer storms. Clear-cutting also increased the riverine carbon (C) export significantly from 95 kg C ha^{-1} yr^{-1} to 183 kg C ha^{-1} yr^{-1} and to 280 kg C ha^{-1} yr^{-1} during pre-treatment, clear-cut and site-preparation periods, respectively. This export represents an important part of the C-balance of a forest in the region. Hydrological effects of clear-cutting included increased snow accumulation by 29 mm (27%) and a modified spring snowmelt. However, the largest effect on the water balance (~189 mm = 31%) was found during summer, when stream runoff was increased due to reduction in evapotranspiration. The drivers of the increased DOC concentrations were identified as changing flow-pathways in riparian soils activating more surficial, DOC rich soil layers, as well as increased soil temperatures that enhanced the DOC availability in riparian soils and therefore increased DOC mobilization from clear-cuts during the summer. In a final step, the impact of these increased, clear-cut induced DOC inputs into a larger scale boreal stream network were investigated by using a mixing model approach. DOC inputs were transferred to downstream sites, which resulted in increases in DOC concentrations at these locations. Further, the modeling approach showed that increases in DOC concentrations can be statistically detected, if the total area harvested within the stream network exceeds threshold values of 11% ($p>0.05$) and 23-25% ($p<0.001$) of the catchment area. Thus, this thesis suggests that threshold values for the maximum percentage of harvested area within a river basin should be implemented into forest planning for boreal catchments that are sensitive to changes in DOC concentrations.

Keywords: Dissolved Organic Carbon (DOC), Forestry, Clear-Cutting, Boreal Forest, Water Quality, Forest Hydrology, Nutrient Mobilization, Soil Temperature.

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Die Endlosigkeit des wissenschaftlichen Ringens sorgt unablässig dafür, dass dem forschenden Menschengeist seine beiden edelsten Antriebe erhalten bleiben und immer wieder von neuem angefacht werden: die Begeisterung und die Ehrfurcht.

Max Planck (1858-1947)

Contents

List of Publications

This thesis is based on the work contained in the following papers, referred to by Roman numerals in the text:

I Schelker, J., K. Eklöf, K. Bishop and H. Laudon (2012). Effects of forestry operations on dissolved organic carbon concentrations and export in boreal first-order streams. *Journal of Geophysical Research*, 117 (G1), G01011.

II Schelker, J., L. Kuglerová, K. Eklöf, K. Bishop and H. Laudon (2013). Hydrological effects of clear-cutting in a boreal forest – Snowpack dynamics, snowmelt and streamflow responses (2013). *Journal of Hydrology,* 484 (0), 105-114.

III Schelker, J., T. Grabs, K. Bishop and H. Laudon. Drivers of increased organic carbon concentrations in stream water after forest disturbance: Separating effects of changes in flow-pathways and soil warming. *(Submitted Manuscript)*.

IV Schelker, J, K. Öhman, S. Löfgren and H. Laudon. Scaling of increased dissolved organic carbon inputs by forest clear-cutting - What arrives downstream? *(Submitted Manuscript)*.

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The contribution of Jakob Schelker (the respondent) to the papers included in this thesis was as follows:

I The respondent was the main person responsible for data handling, data analysis, model development, interpretations, writing and publishing.

II The respondent was the main person responsible for study design, data collection, data analysis, interpretation, writing and publishing.

III The respondent was the main person responsible for data collection and analysis, model development, interpretation and writing.

IV The respondent was the main person responsible for study design, data collection and analysis, model development, interpretation and writing.

Abbreviations

Abbreviation	**Description**
a	Model parameter describing the transmissivity profile, factor
$A_{cc\text{-}4}$	Percentage of area harvested in the CC-4 catchment
$A_{critical}$	Threshold value of the percentage harvest in a river basin
A_i	Percent of total catchment area that is clear-cut harvested or that acts as a control for site *i*, *(i= site; harvest, control, ...)*.
b	Model parameter describing the transmissivity profile, exponent
C	Carbon
c	Solute concentration
c_0	Solute concentrations at the soil surface (z=0)
c_{out}	Concentration at a stream outlet
c_{runoff}	Solute concentration in the stream
d	Conversion factor, defined as the reciprocal of $A_{cc\text{-}4}$
DOC	Dissolved organic carbon
f	Shape-parameter defining the shape of the soil DOC profile
GW	Groundwater
h	Waterlevel in the stream
M_i	Mass flux of a solute from site *i*, *(i= site; harvest, control, ...)*
PCA	Principal Component Analysis
Q	Stream Discharge
q	Lateral inflow into the stream at depth z
Q_{out}	Discharge at a stream outlet
z	Soil depth

1 Introduction

1.1 Dissolved Organic Carbon

Dissolved Organic Carbon (DOC) describes the organic solute composition of a sample. Even though DOC does not consist of a single chemical substance, the importance of DOC in defining stream ecosystems arises from its biogeophysical properties.

A major characteristic of DOC in stream water is given by the interaction with the acid state of the stream environment. DOC in natural waters is dominated by humic substances, such as hydrophilic and hydrophobic acids (Cronan & Aiken, 1985; McLaughlin *et al.*, 1996; Hruska *et al.*, 2003). DOC exerts therefore a direct control on the acid state of streams and lakes (Kortelainen, 1992; Laudon *et al.*, 2000; Erlandsson *et al.*, 2010), which in turn directly impacts on biota in aquatic ecosystems (Bridcut *et al.*, 2004; Serrano *et al.*, 2008), often as a result of the increased mobilization of highly toxic inorganic monomeric aluminum (Cory *et al.*, 2006; Baldigo *et al.*, 2007).

Furthermore, DOC acts as a transport vector for numerous metals and contaminants. Examples for this capability are given by the strong binding of the inorganic forms of mercury on DOC (Haitzer *et al.*, 2002; Skyllberg *et al.*, 2006). This binding results in strong correlations of Hg(II) and DOC concentrations in stream water that are observed in many meso-scale catchments (Dittman *et al.*, 2009; Riscassi & Scanlon, 2011; Burns *et al.*, 2013). Additional examples of the ability of DOC to enhance the mobilization of metals and pollutants are the linking of the transport of various trace metals, such as arsenic, cobalt, vanadium and lead to DOC concentrations in stream water (Huser *et al.*, 2011), as well as the affinity of persistent organic pollutants to DOC (Bergknut *et al.*, 2010).

Besides these chemical characteristics, fluxes of DOC leaving terrestrial ecosystems have recently been recognized as an important part of the Carbon

(C) balance of various ecosystems (Cole *et al.*, 2007; Battin *et al.*, 2009; Wallin *et al.*, 2013). However, whereas exports of DOC from terrestrial sources are commonly dominated by older, more degraded fractions (Evans *et al.*, 2007; Dinsmore *et al.*, 2010), minor proportions of DOC may also be bioavailable and therefore act as a nutrient. Microbial uptake of labile DOC, such as Carboxylic Acids, Amino Acids and Carbohydrates from terrestrial sources is thereby a direct pathway into the aquatic foodweb (Vannote *et al.*, 1980; Berggren *et al.*, 2009). Furthermore, labile DOC may originate from restructuring of larger DOC compounds by UV-radiation in the water column (Tranvik & Bertilsson, 2001), that becomes bioavailable at downstream sites. Nevertheless, this breakdown of more stable, recalcitrant DOC may be partly counteracted by the ability of DOC to attenuate light in DOC-rich waters. This light limitation has recently been identified as a major factor limiting primary productivity of nutrient poor lake ecosystems (Karlsson *et al.*, 2009).

Given the biogeochemical and ecological importance of DOC, understanding the spatio-temporal dynamics in stream water is of fundamental interest. Furthermore, additional alterations of stream DOC dynamics following natural and anthropogenic disturbances of the terrestrial ecosystem need to be better understood to evaluate their impact on aquatic ecosystems.

1.1.1 Mobilization of DOC into Streams

DOC mobilization, defined as the transport of organic matter from the terrestrial into the aquatic ecosystem, is primarily governed by water flows that connect the streams with different DOC source areas. Such source areas are commonly consisting of soils that are rich in soil organic matter, such as peat rich riparian zones and wetlands (Aitkenhead *et al.*, 1999; Canham *et al.*, 2004). Large soil carbon stocks are most abundant in high altitude boreal regions (Batjes, 1996; Jobbágy & Jackson, 2000) which are also among the regions with the highest stream DOC concentrations (Laudon *et al.*, 2012).

DOC originating from upland soils can also be an important component of the stream DOC concentrations. This source of DOC appears to be especially prominent in streams of the temperate, humid eco-zone (Raymond & Saiers, 2010), in which peat soils in stream near zones are less abundant. In these systems the connectivity of the upland soils to the streams (McGlynn & McDonnell, 2003) is of large importance for DOC mobilization.

The upland DOC contributions may further be dependent on additional processes affecting the mobility of DOC on its way from the organic rich upper soil horizons to the stream. These processes affecting the mobility and therefore the transports of OM in mineral soils include adsorption and desorption, precipitation and dissolution, complexation and decomplexation, diffusion, decomposition, as well as protonation and deprotonation (Kalbitz *et al.*, 2000). Many of these processes are dependent on environmental conditions such as soil temperature and soil pH (Andersson & Nilsson, 2001). Consequently, the mobility of DOC in the soil solution was found to be directly affected by the acid state of soils (Kerr & Eimers, 2012) so that a higher soil pH (as e.g. found as a result from recovery from acidification from lowered SO_4 deposition) is assumed to increase DOC mobility (Löfgren *et al.*, 2010). In turn, this mechanism is also believed to affect long term trends of stream DOC concentrations in regions that are recovering from a high acid deposition in the past (Evans *et al.*, 2006; Monteith *et al.*, 2007).

However, in catchments of the northern humid and boreal eco-zone that have a pronounced peat accumulation in riparian zones originating from C-accumulation since the last glaciation, stream near sources of organic matter are considered the most important contributor to stream DOC (Creed *et al.*, 2003; Canham *et al.*, 2004). In these systems runoff generation is believed to be primarily driven by the 'transmissivity feedback' mechanism (Bishop, 1991; Kendall *et al.*, 1999). This mechanism is based on the strong increase of saturated hydraulic conductivities towards the soil surface, that are common in boreal catchments (Seibert *et al.*, 2003). If water pulses from rain or snowmelt events enter these soils, the soil profile becomes progressively saturated. Subsurface flow is then running off laterally in more surficial soil layers of riparian soils until it reaches the stream channel (Bishop *et al.*, 2011; Seibert *et al.*, 2011).

DOC concentrations in shallow groundwater (GW) are often found to be highest at the soil surface and decreasing with soil depth in these systems (Bishop *et al.*, 2004; Lyon *et al.*, 2011). The transport of DOC into the stream is therefore directly linked to the processes of runoff generation. It is assumed to be primarily driven by the increase in shallow GW levels during events, such as summer episodes or the spring freshet. These events are activating more surficial flow-pathways with high DOC concentrations of riparian soils (Seibert *et al.*, 2009; Grabs *et al.*, 2012).

Commonly DOC concentrations are therefore found to be positively related to stream flow (Hinton *et al.*, 1997; Schiff *et al.*, 1998; Bishop *et al.*, 2004; Laudon *et al.*, 2004), often even following power functions between discharge and DOC concentrations (Seibert *et al.*, 2009). This underlines the pivotal role of the hydrological driver on DOC mobilization into boreal streams. Consequently, long-term trends of DOC concentrations in Scandinavia were found to be more dependent on stream discharge than on any other driver (such as e.g. changes in SO_4 concentrations) (Erlandsson *et al.*, 2008).

Additional factors that are believed to regulate DOC mobilization besides the hydrological control include soil temperature (Hornberger *et al.*, 1994; Freeman *et al.*, 2001). This hypothesis has been supported by recent research from northern Sweden that conceptualized the combined effects of runoff generation and soil temperature dynamics on DOC mobilization (Köhler *et al.*, 2009; Winterdahl *et al.*, 2011a).

Furthermore, deep soil frost has been found to increase stream DOC levels in boreal catchments during the spring (Haei *et al.*, 2010; Ågren *et al.*, 2012). This suggests that also winter conditions are relevant for the DOC export from catchment soils during the spring and summer.

Model conceptualizations used to investigate DOC dynamics in stream water span from simple mixing model approaches in which different DOC source areas are represented as 'end-members' of the landscape (Hooper *et al.*, 1990; Inamdar & Mitchell, 2006; Laudon *et al.*, 2011a) to conceptual models of hillslopes (Weiler & McDonnell, 2006), as well as rainfall-runoff models (Boyer *et al.*, 1996; Schelker *et al.*, 2011; Xu *et al.*, 2012) to fully process-based models (Futter *et al.*, 2007). However, few of these conceptualizations have been used to investigate the changes of stream water chemistry in boreal streams resulting from land-use, such as forest harvesting.

1.1.2 Effects of Forest Clear-Cutting on DOC Concentrations

Stream DOC concentrations have been shown to be strongly affected by catchment perturbations from intensive land management, such as forest clear-cutting (Nieminen, 2004; Laudon *et al.*, 2009; Bolan *et al.*, 2011; Stanley *et al.*, 2012). A major part of the enhanced leakage of DOC is believed to be a result of changes in the hydrological cycle (Kreutzweiser *et al.*, 2008), that are commonly observed as a result of forest removal (Hornbeck *et al.*, 1997; Andréassian, 2004). The hydrological effects are attributed to changes in snow accumulation and melt (Moore & Scott, 2005; Varhola *et al.*, 2010; Penn *et al.*, 2012), as well as changes in the water balance that are substantiated in the lower evapotranspiration of clear-cuts compared to intact forest stands during summer (Bosch & Hewlett, 1982; Stednick, 1996; Andréassian, 2004; Brown *et al.*, 2005).

Additional factors that have been found to enhance the effects of clear cutting on stream DOC concentrations are the increased decomposition of soil organic matter (Liski *et al.*, 1998; Lamontagne *et al.*, 2000; Kreutzweiser *et al.*, 2008) and other changes in soil conditions, such as observed increases in soil temperature (Olchev *et al.*, 2009) and soil moisture. Furthermore, a higher availability of soil C may be prevalent after harvests, if logging residues are left on site (Hyvonen *et al.*, 2000; Hazlett *et al.*, 2007). Such C inputs to soils could contribute directly to the mobile pool of DOC in soils that can be transported to streams. Alternatively, additions of labile C from logging residues could favor an increased breakdown of soil organic matter, similar to the hypothesized mechanism of ‘priming’ (Dalenberg & Jager, 1989), that, in turn, would increase the concentration of mobile DOC in the soils solution.

However, whereas the effects of clear-cutting on stream DOC concentrations have been quantified in the past, there is a lack of linking the detailed process understanding on hydro-biogeochemical functioning of boreal catchments to these disturbances. Furthermore the question of how streams draining larger landscapes of intensely managed boreal forests transport and process DOC within the stream network constitute additional knowledge gaps.

1.2 Forestry and Forest Disturbance

Forestry is of large importance for the Swedish economy. Of the total Swedish land area (40.8 10^6 ha) 55% are classified as productive forest land. In 2009 the Swedish forest sector (forest industry and forest product industry) equaled a total value of 2.2 % of the Swedish Gross Domestic Product and 11.7 % of the value generated by the production sector (Swedish Forest Agency, 2012).

The primary form of forest management in Sweden is forest clear-cutting that is followed by specific actions to promote forest regeneration. The later normally include site-preparation, such as disk-trenching and sowing or replanting of tree seedlings.

Furthermore, sustainable, but intensive forest management has been suggested as a strategy to increase biomass production and, accordingly, mitigate future environmental perturbations through the increased use of renewable energy sources (Akselsson *et al.*, 2007; Egnell *et al.*, 2011). However, this forest management strategy also bears risks for aquatic ecosystems that may be impacted by such intensified practices (Laudon *et al.*, 2011b).

1.3 Paired Catchment Design

The paired catchment study design has a long tradition in forest hydrology. The basic design is to select two nearby catchments that are as similar as possible and of which one catchment is treated after a pre-treatment period whereas the other catchments remains as an untreated reference site (Hewlett, 1971). Common criteria for defining this similarity are: catchment size, morphology, geology, climatic forcing and land use (Andréassian, 2004).

Early studies using the paired catchment design reach as far back as the beginning of the 20th century, with studies such as the *'Wagon Wheel Gap'* in Colorado (Bates and Henry 1928, cited in Bosch & Hewlett, 1982). But whereas earlier studies were primarily focusing on the changes in water uptake by forests after forest disturbance, the later experiments with the same design also included detailed studies on nutrient cycling. One such later example is given by the '*Hubbard Brook Experimental Forest*', New Hampshire which was established in 1955. At this site the increased leaching of nutrients such as nitrogen and major ions into stream water after forest removal and consecutive suppression of the regrowing vegetation were quantified (see Bormann *et al.*, 1968 for a classical study). Later studies at this site also included research on other ecosystem perturbations, such as acid rain (Likens *et al.*, 1996) or the impact of climate change (Campbell *et al.*, 2011).

The paired catchment design has been followed by numerous studies using the same approach (Hornbeck *et al.*, 1993; Stednick, 1996; Andréassian, 2004; Jones & Post, 2004; Brown *et al.,* 2005). However, Buttle *et al.,* (2000) point out that similar experiments from the boreal eco-zone are sparse, even if land-use by productive forestry is of very high importance for these specific regions. This thesis is therefore based on data collected in the *Balsjö paired-catchment study* in the boreal regions of northern Sweden which are used to investigate the effects of forest clear-cutting on water quality. The specific tasks included in this thesis are described in the following section.

1.4 Study Objectives

Given the importance of both water quality and forestry for boreal regions, the objectives of this thesis were defined as:

- Quantifying the effects of forest clear-cutting and site-preparation on stream DOC concentrations in boreal first-order catchments (Paper I),
- Evaluating the importance of the riverine C-export of a clear-cut forest for the C-balance of a forest in the region (Paper I),
- Quantifying the changes in the water-balance of a boreal first-order catchment that is clear-cut harvested (Paper II),
- Evaluating the importance of altered snow accumulation and the spring freshet for water yields in harvested first-order catchments (Paper II),
- Investigating the role of various drivers (flow-pathways, soil temperature and soil moisture) in controlling the changes in DOC concentrations after forest disturbance (Paper III),

- Evaluating the combined effects that increased DOC concentrations and increased discharge have for larger streams in a stream network that is subject to forestry operations (Paper IV), and
- Giving recommendations for better forestry practices in sensitive boreal stream networks (Paper IV).

In summary, this thesis aims at promoting a deeper understanding of the effects and impact of ecosystem disturbance by forest management on a meso-scale boreal catchment in Scandinavia.

2 Methods

2.1 Study site

All papers included in this thesis (I-IV) were based on primary data collected in the *Balsjö paired-catchment study* in northern Sweden. The site is located approximately 70 km from the Baltic sea coast (N 64° 01’ 37’’, E 18° 55’ 43’’) and consist of 6 stream sampling sites covering a 3rd order stream network with a total catchment area of 22.9 km^2.

Four of the sampling sites are located along first-order streams draining the most northern sub-catchments of the watershed. These catchments include two sites that were partly harvested in 2006 (NO-5 and CC-4), as well as two reference sites of different size and character (RS-3 and NR-7). Furthermore, the NO-5 site is a downstream site to NR-7 (Fig. 1).

Further, two downstream sites are located along the *Balån River* which also drains the first-order streams. BA-2 is covering a 3rd order stream with a catchment area of 8.7 km^2 located upstream of a larger wetland area with a pond with open water. BA-1 is located downstream of the wetland and represents the main outlet of the 22.9 km^2 catchment (Fig. 1).

The soils within the Balsjö catchment are typical for the boreal regions of Fennoscandia and consist of till dominated substrates that have a glacial origin. Upland soil types are orthic podsols, whereas wetter soils are classified as histosols (Löfgren *et al.*, 2009). The thin soils are underlain with bedrock, that consists of late-orogenic pegmatite with aplatic grantie and aplite (Löfgren *et al.*, 2009).

The long-term annual average precipitation in the area is 554 mm and the mean air temperature is 0.6 °C (Alexandersson *et al.*, 1991). However, as noted in Paper II, the mean precipitation in Balsjö during the hydrological years of 2004-2011 averaged at a slightly higher value of 613 (±67) mm. Snow usually covers the ground between November and May; the growing season (mean air temperature above 5 °C) is commonly between 150 and 180 days long (Löfgren *et al.*, 2009).

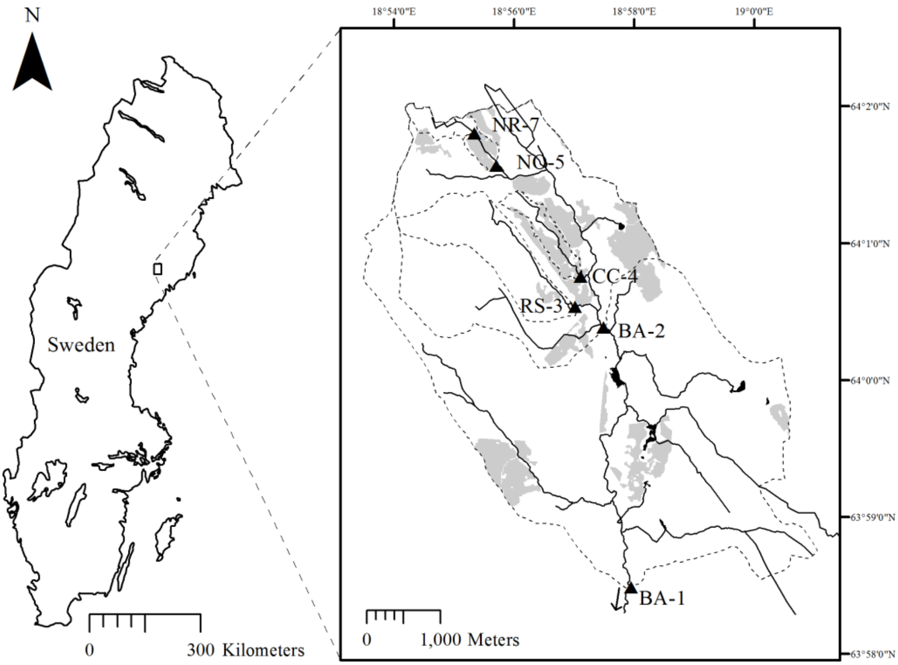

Figure 1. The Balsjö paired catchment experiment in northern Sweden. Solid black lines represent the stream network, dashed lines the catchment boundaries; black pyramids indicate the location of sample drawing (all sites) and stream gauges for the BA-1, CC-4, NO-5 and NR-7 catchments, respectively. Areas harvested during 2000-2011 are shown as grey shading; solid black areas show ponds with open water. This figure is also included in Paper IV.

The vegetation in the Balsjö catchment is typical for the Swedish boreal forest. Dry upland locations are dominated by Scots pine (*Pinus sylvestris*), whereas Norway spruce (*Picea abies*) is most abundant in the lower and middle elevations of the catchment. Understory vegetation is dominated by dwarf shrubs such as *Vaccinium* species or cowberry (*Empetrum* spp.). In wet valley bottoms and along streams birch (*Betula* spp.) is the most common tree species. The ground vegetation in these areas is characterized by various mosses (e.g. *Sphagnum* spp., *Polytricum* spp.) (Löfgren *et al.*, 2009; Paper II).

For three of the first-order catchments (NO-5, CC-4, RS-3) a more detailed description of the relative abundance of the three most common tree species and the standing volumes of the forest prior to the final felling performed in 2006 is given by Eriksson *et al.*, (2011) (Table 2).

Table 1. *Catchment characteristics of all 6 Balsjö catchments (modified after Paper IV).*

Site Name	Abbreviation	Catchment Area (ha)	Proportion Wetland (%)	Proportion Open Water (%)
Balån River 1 Outlet	BA-1	2291	15	0.38
Balån River 2 (Upstream Wetland)	BA-2	868	10	0.08
Southern Reference	RS-3	156	3	0.00
Southern Clear Cut	CC-4	41	7	0.00
Northern Catchment	NO-5	40	12	0.00
Northern Reference	NR-7	24	16	0.00

Final felling in the NO-5 and CC-4 catchments was performed in March 2006. These experimental harvests followed the Swedish recommendations of good forest practices, but all measures of environmental protection were planned and performed by the contractors (Löfgren *et al.*, 2009). The harvests were conducted on frozen ground. Along the stream reach of the NO-5 catchment where harvest were performed, a discontinuous riparian buffer strip with an approximate width of <10 m on each side of the stream was left. In the CC-4 catchment, no such buffer was left. Clear-cut harvests were followed by site-preparation, which was performed in spring 2008. Site-preparation included disk trenching to a soil depth of approximately 5-15 cm and sowing of pine trees (*pinus sylvestris*) in the open trenches, in which the mineral soil was exposed. Site-preparation disturbed the ground vegetation, which was observed to shift from shrub species to grasses (*Poaceae*) and sedges (*Cyperaceae*) (Paper II). A more detailed description of the experimental harvests in the Balsjö first-order streams is given by Löfgren et al., (2009), whereas Paper I and II of this thesis give a more detailed description of the changes after site-preparation.

Forest management in the larger BA-1 catchment followed the planned practices by the forest owners. Harvesting intensity (here defined as the percentage of the catchment area that has been clear-cut harvested) varied therefore over time. Satellite based estimates (see Paper IV, for a full description of this method) of clear-felled areas increased from 2.5% and 4.6% in 2004 to 11.2% and 17.5% in 2011 in the BA-1 and BA-2 catchments, respectively. Harvests of the first-order catchments included a percentage of 64% in CC-4 and 35% in NO-5, both performed in 2006 with no prior harvests. Further, the harvesting intensity increased from 2.8% (2006) to 4.8% (2007) in the NR-7 control catchment, followed by an additional harvest of the most northern slope of the NR-7 reference catchment in 2011, reaching 16.4% of the catchment area of NR-7.

Table 2. *Vegetation data for the three sub-catchments RS-3, CC-4 and NO-5 before the harvests in 2006 (modified after Eriksson et al., 2011).*

Sub-catchment	Area (ha)	Stand age (y)	Stem volume (m^3 ha^{-1})	Norway spruce (%)	Scots pine (%)	Other (%)	Site index, H_{100} (m)
RS-3	156	41	74	41	36	24	18.6
CC-4	41	97	158	38	53	9	16.9
NO-5	40	90	163	50	40	9	17.4

2.2 Data Collection and Analysis

2.2.1 Hydro-meteorological Measurements

Hydrologic measurements were performed at the CC-4, NO-5 and the NR-7 sites since the beginning of the Balsjö paired catchment study in 2004 (Sørensen *et al.*, 2009b). At each stream, gauging stations with a 90° V-notch weir were installed. Water levels were then measured by three measurement systems, consisting of two Trutrack staff loggers (Trutrack Inc., New Zealand) that independently recorded water levels and water temperature with an hourly interval, as well as a pressure-traducer (MJK A/S, Denmark) that was connected to a Campbell scientific data logger system (Type CR510 for CC-4 and NO-5, respectively; CR10X for NR-7). Raw data was then calibrated by manual water level measurements that were commonly performed during stream sampling. Discharge at CC-4, NO-5 and the NR-7 was then quantified by using rating curves to calculate stream discharge.

Rating curves for the Balsjö catchments have been first developed by Sørensen et al., (2009b), but were updated with additional data from bucket and salt-dilution measurements that were performed between 2008 and 2011 (see also Paper I and II). Rating curves were checked annually and there were no signs of systematic shifts over time. An example of a rating curve is given in Fig. 3.

Discharge measurements at the site BA-1 began in spring 2006 and were performed by using Trutrack staff loggers (Trutrack Inc., New Zealand) that were installed at the inlet of a culvert that channels the stream below the main road. A rating curve based on salt-dilution measurements of discharge was developed. Specific discharge data for BA-1 showed good agreement with the data from the upstream sites. Therefore discharge estimates for the time before 2006 were inferred by interpolation from the upstream sites.

Additional meteorological data, such as stream and air temperatures as well as precipitation was derived from measurements at the gauging stations at CC-4, NO-5 and NR-7. Data series for air temperature and precipitation were then completed by interpolation from surround meteorological stations operated by the Swedish Meteorological and Hydrological Institute (SMHI), as well as the nearby Krycklan-Svarberget LTER site (see Paper II for specific information).

Figure 2. V-notch weir at the outlet of the NR-7 forest catchment during a rain episode in October 2011. All logger systems for recording waterlevels are attached to the wooden beam reaching over the stream. The DOC concentration at this site during this specific occasion (2011-10-19) was 29.8 mg L^{-1}.

Groundwater (GW) levels, as used in Paper III, were measured at a total of 23 locations that were placed in the riparian zone with a distance of 0.2 to 60 m from the stream within the CC-4, NO-5 and NR-7 catchments, respectively. At each GW site, Trutrack (Trutrack Inc., New Zealand) water level loggers were installed in PVC-pipes. The loggers recorded the water level at an hourly basis. Each GW time series was then calibrated with manual water level observations originating from manual water level measurements that were performed every two weeks during May to October 2009. A more detailed description of GW level measurements and the data selection for modeling purposes is given in Paper III.

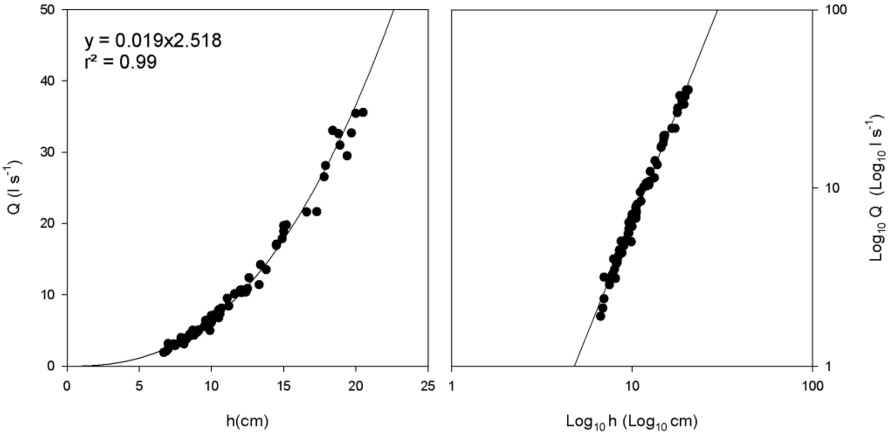

Figure 3. Rating curve for the V-notch weir of the CC-4 clear-cut catchment. *Q* denotes discharge measured by bucket or salt-dilution measurements, whereas *h* denotes the manually measured waterlevel at the V.

Soil temperature and soil moisture, as used in Paper I and III, were measured on a western slope in the clear-cut within the lower part of the NO-5 catchment and within the nearby control forest of the NR-7 catchment. Both sites have a similar slope and an approximate distance of 40-50 m from the stream. Measurements were performed by a series of soil temperature probes (TOJO Skogsteknik, Sweden) that were installed in the soil profile at a soil depth of 15 cm, 30 cm and 50 cm, respectively (Fig. 4). Volumetric soil moisture was measured with Campbell-Scientific time-domain reflectometry (TDR) probes (model CS 616) at the soil depth of 20 cm and 50 cm at both sites (Fig 4.). A more detailed description of soil temperature and soil moisture measurements, as well as data pre-processing and averaging, respectively, is given in Papers I and III.

Figure 4. Installation of soil moisture and soil temperature probes within the NR-7 catchment in Balsjö (photo: Peder Blomkvist). The ruler visible in the picture denotes a total length of 1 m. Temperature probes (15, 30 and 50 cm soil depth) are visible in the center, whereas soil moisture probes (30 and 50 cm; 3-4 probes at each depth) are located at the left and right.

2.2.2 Water Sampling and Analysis

Regular stream sampling was performed as grab sampling at all 6 Balsjö sites. Samples were taken with a 4-week interval during winter (November to March), followed by a higher (up to 2 samples per week) interval during the spring freshet and a 2-week sampling interval during summer and fall. Sampling began in spring 2004 and is continued until present (spring 2013).

High frequency data used in Papers I and III was collected by ISCO automated sampler units (Teledyne Isco, Inc; USA). The units were setup during spring, prior to the first increases in discharge of the spring freshet and were operated continuously until the fall (approximately until mid-October; with shorter periods of malfunctioning) for the sites RS-3, CC-4, NO-5 and NR-7 during the years 2008-2010. Sampling frequencies were always kept at a minimum of one sample every 2 days during low flow conditions, whereas medium and high flow conditions were sampled at a frequency of 12 h in 2008, 8 h in 2009, and 24 h in 2010. A more detailed description of the automated stream sampling is given in Paper I.

All samples were frozen within 2-3 days and analyzed using a Shimadzu TOC 5050 prior to 2006 and a Shimadzu TOC_{VCPH} after spring 2007. Samples were not filtered prior to analysis. However, it is assumed that total organic carbon concentrations represent DOC concentrations, because the dissolved fractions commonly dominate the organic carbon concentrations (>95% DOC; see Laudon *et al.*, 2011a).

2.2.3 Statistical Approaches

Statistical tests applied in the research of this thesis included both, parametric and non-parametric tests. In Paper I a non-parametric Kruskal-Wallis one way analysis of variance on ranks (ANOVA-R) which was combined with Dunn's test was used to investigate if significant differences in median values of DOC concentrations occurred. This is in contrast to earlier studies that have used methods such as the Randomized Intervention Analysis (RIA) (Löfgren *et al.*, 2009; Sørensen *et al.*, 2009a) or separate parametric tests for each hydrological event (Laudon *et al.*, 2009) to quantify differences in solute concentrations in the Balsjö catchments. However, the ANOVA-R approach was chosen, because the additional high frequency sampling performed for DOC resulted in varying sample sizes, at the same time as the datasets were not normally distributed. The ANOVA-R approach accounted for these assumptions (see Paper I for more details).

The statistical tests used in paper II and IV included primarily descriptive statistics, such as the Student *t-tests* for evaluating whether differences in mean values were significant. Whereas these tests used in Paper II aimed to describe the primary data, the approach performed in Paper IV also included a stepwise increase of modeled DOC concentrations to investigate when changes become significant. Furthermore these data were additionally tested by a non-parametric Wilcoxon rank-sum test.

Statistical modeling in Paper III included simple linear regression models to evaluate the role of various hypothesized drivers on stream DOC concentrations. But whereas the use of this method is limited by the potential co-dependence of predictor variables, a principle component analysis (PCA) was used as an addition. The PCA method uses the orthogonal variation in a dataset to estimate how closely the different variables correlate in a linear, orthogonal model. The approach is therefore not sensitive for inter-correlated predictor variables. Additional confirmation of simple linear regression models used to quantify the effect of soil warming on model residuals of the RIM model was derived by also applying non-parametrical tests, such as Pearson's correlations and Spearman rank correlation.

Additional information on the subdivision of datasets by events (such as pre- and post-harvest, respectively) as well as specific definitions of seasons used for statistical analysis are given in each of the specific Papers.

2.3 Modeling Approaches

Whereas a large part of this thesis was based on primary data collected in the Balsjö catchment, different model conceptualizations were involved to test additional hypothesis included in papers III and IV. The different conceptualizations were generally developed according to Occam's razor, that is to say, that the *'simplest explanation that can account for a phenomenon is the best explanation'* (Weiler & McDonnell, 2006). Consequently, model complexity was kept at a minimum while the current process understanding was considered, if necessary for the given scale and model purpose. Hence the riparian flow concentrations integration model (RIM; Seibert *et al.*, 2009) was chosen to simulate the changes in flow-pathways in Paper III, whereas a simpler mixing-model approach was developed to simulate the downstream transport of DOC in Paper IV.

2.3.1 Riparian Flow Concentration Integration Model (Paper III)

The riparian flow concentration integration model (RIM) (Seibert *et al.*, 2009) was used in Paper III to simulate the effects of changing flow-pathways in riparian soils on stream DOC concentrations. This model conceptualization is based on the 'transmissivity feedback mechanism' (Bishop *et al.*, 2004) that describes the discharge in the stream (Q) as the integral of the lateral inflows (q) of shallow GW through the riparian soils (Grabs *et al.*, 2012).

$$Q = \int_{z0}^{z1} q(z)dz \qquad (1)$$

By assuming an exponential decrease of the saturated hydraulic conductivity with soil depth, the water flows can be formulated as $q(z) = ae^{bz}$, with a and b being model parameters describing the shape of the transmissivity profile of the soil (Seibert *et al.*, 2009). Furthermore, the shape of the riparian DOC concentration profile can be described as $c_{soilwater}(z) = c_o\, e^{fz}$, with c_0 being the concentration at the soil surface and *f* being the shape-parameter (Winterdahl *et al.*, 2011b). Stream concentrations of DOC can then be inferred from the lateral inflows and the DOC soil profile using Equation 2 given by Seibert et al., (2009):

$$c_{runoff} = \frac{L}{Q} = \frac{\int_{z0}^{z1} q(z)c_{soilwater(z)}dz}{\int_{z0}^{z1} q(z)dz} \qquad (2)$$

with c_{runoff} being the concentration of the solute in stream water and L being the solute load. The analytical solution of the integral is then given as (Eq. 3) (Seibert *et al.*, 2009; Winterdahl *et al.*, 2011a):

$$L = c_0 \frac{\left(\frac{a}{b}\right)^{1-n}}{n} Q^n \,, \quad \text{with } n = \frac{b+f}{b} \qquad (3)$$

A detailed description of the model parameterization using measured the transmissivity profiles derived from GW levels and stream flow data, as well as the fitting of the shape-parameter *f* is given in Paper III.

2.3.2 Mixing Model Approach (Paper IV)

The mixing model approach used in Paper IV was based on a linear mass transfer downstream assuming conservative mixing. Further, no additional loss or gain processes were considered. The concentration at a downstream site (C_{out}) was modeled for each time step as (Eq. 4):

$$C_{out} = (M_{harvest}\, A_{harvest} + M_{control}\, A_{control})\, {Q_{out}}^{-1} \qquad (4)$$

with Q_{out} being the specific discharge at the outlet, M_i being solute mass export (defined as $M_i = Q_i\, C_i$, for the site i; i=*harvest*, *control*, etc..) and A_i being the fraction (%) of the total area that was harvested or acts as a control, respectively. $C_{harvest}$ was defined as the concentration of a 100% harvested catchment. This was calculated using the DOC concentrations from the sites CC-4 and $C_{control}$ and assuming a linear increase of the difference between both sites following a conversion factor *d* (Eq. 5):

$$C_{harvest} = C_{control} + (C_{CC-4} - C_{control})\ d \qquad (5)$$

with the conversion factor *d* being defined as the reciprocal of $A_{CC-4,}$ where the latter is the percentage of catchment area harvested in the CC-4 catchment.

Similar to Paper I, $C_{control}$ was calculated as the mean concentration of the two Balsjö first-order streams that were not harvested (RS-3 and NR-7). After 2011, when additional harvests were performed within NR-7, data from RS-3 was used exclusively. $Q_{harvest}$ was calculated by using the difference in *Q* of the two stream gauges NR-7 and NO-5. This nested downstream catchment[1] of NR-7 represents a harvest area 88% of the catchment area.

Furthermore, Q_{out} was modeled for each time step as the sum of $Q_{harvest}$ * $A_{harvest}$ and $Q_{control}$ * $A_{control}$. This allowed compensating for potential differences in residence times, as well as for estimating discharge for site BA-2, where no discharge data was available. A simple comparison of the modeled Q_{out} for the site BA-1 with the measured discharge at this site, as well as additional model assumptions are described in Paper IV.

1. This catchment is called BS-5 in Paper I

3 Results and Discussion

This thesis investigates how forest clear-cutting affects the hydrology and DOC concentration and efflux, respectively, of a boreal stream network. Paper I explored the effects of clear-cutting on DOC concentrations and riverine C-exports in the Balsjö first-order streams. In Paper II the importance of the altered snow accumulation on the changes of the water balance of two selected first-order streams were investigated. Paper III further examined what drivers are causing the observed increases in DOC mobilization from catchment soils to streams. In Paper IV the downstream transport of increased DOC inputs by clear-cutting into the stream network were evaluated. The main findings of each of these studies and their implications are discussed below.

3.1 Clear-Cutting Effects on DOC Concentrations and Export

The results of Paper 1 show that clear-cutting increased the median DOC concentrations significantly from 15.9 to 20.4 mg L^{-1}, which represents a net-increase (treatment vs. control) of 3.0 mg L^{-1} in the 2006-2007 measurement period. Site-preparation performed to govern forest regrowth had an even stronger effect on DOC concentrations resulting in an increase of 7.2 mg L^{-1} (20.4 to 27.6 mg L^{-1}) in the site-prepared catchments, whereas the control sites increased slightly from 17.4 to 21.4 mg L^{-1} during 2008-2009 (Fig. 5).

These results are in broad agreement with the literature that highlights the impact of clear cutting on stream DOC levels that is maintained for at least one decade after the harvest (Kortelainen & Saukkonen, 1998; Lamontagne *et al.*, 2000; Nieminen, 2004; Piirainen *et al.*, 2007; Kreutzweiser *et al.*, 2008; Laudon *et al.*, 2009). Even though these changes in DOC concentrations as a response to forestry operations were found to be larger than in some of studies mentioned above, the differences may be attributed to the specific climatic region and soil C-pools that predetermine DOC levels in the northern landscape (Aitkenhead *et al.*, 1999; Ågren *et al.*, 2008; Laudon *et al.*, 2012).

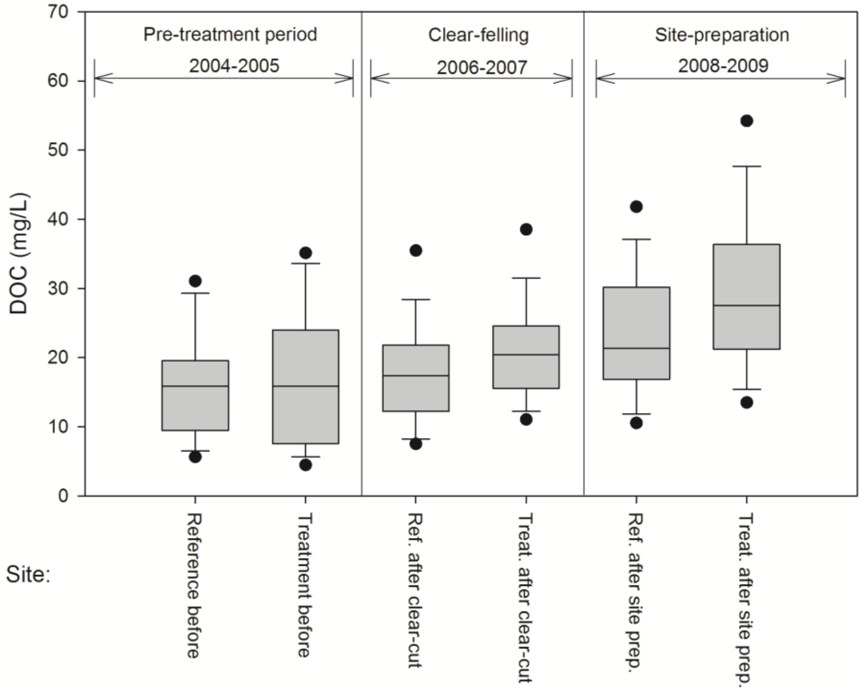

Figure 5. Boxplot of mean DOC concentrations in stream water for the two treated and the two control sites for the different time periods during which forestry operations were performed at the Balsjö paired catchment (from Paper I). Gray boxes represent the 25th to 75th percentiles; error bars indicate the 10th to 90th percentile. Solid black points indicate the 5th to 95th percentiles. The median is shown as a horizontal line. More information, such as sample sizes, etc. is given in Paper I.

Consequently, the impact of clear-cutting on lateral stream C-exports was also substantial. Riverine organic C-fluxes increased significantly by 100% after clear cutting and by 79% after site preparation due to the combined increase in concentrations and discharge. Similarly large riverine organic C-fluxes (183 kg C ha^{-1} yr^{-1} after clear-cutting and 280 kg C ha^{-1} yr^{-1} after site preparation) are commonly only reported for streams draining mires and peatlands (Roulet *et al.*, 2007; Nilsson *et al.*, 2008; Dinsmore *et al.*, 2010; Wallin *et al.*, 2013). However, if the results of Paper I are compared to a study from southern Finland, were the effects of clear-cutting on C-export from drained peatlands were evaluated (Nieminen, 2004), the given numbers agree well with the fluxes reported for the frost-free season (36-110 kg C ha^{-1}; see Nieminen, 2004). In turn, this underlines the significance of peat rich source areas of DOC in the harvested catchments for riverine C-exports.

Furthermore, the riverine C-fluxes were found to represent an important fraction of the annual C-balance of a forest in the region (10-28% of the net ecosystem exchange). These fluxes were, further, found to be highly dependent on changes in discharge (Q accounted for 90% of the change in the C-flux after clear-cutting and 79% after site-preparation, respectively). In turn this supports the need to investigate the question of when these increases in discharge take place (addressed in Paper II) and what additional drivers are responsible for the large temporal dynamics observed in DOC concentrations (addressed in paper III).

3.2 Hydrological Changes after Clear-Cutting

In Paper II, two of the Balsjö first-order streams (CC-4 and NR-7) of which one (CC-4) was clear-cut harvested in 2006 were selected to specifically investigate the hydrological effects of clear-cutting. The results show that clear-cutting increased snow water equivalents (SWEs) on average by 29 mm (27%) in the clear-cut. These results are in agreement with other studies (Golding & Swanson, 1986; Murray & Buttle, 2003; Ottosson Löfvenius *et al.*, 2003; Winkler *et al.*, 2005; Jost *et al.*, 2007; Varhola *et al.*, 2010) that have shown similar effects in snow accumulation between clearings and closed forest canopies, suggesting that differences in spring runoff volumes may be also prevalent.

Snowmelt runoff increased by 39% and 27% in the harvested CC-4 catchment (reference= 144 mm and 121 mm) during 2008 and 2009, respectively, but no significant differences in stream runoff between both catchments was observed during spring 2007, 2010 and 2011. Furthermore, the overall differences in snowmelt runoff between the two catchments were smaller than the year-to-year variation, resulting in no significant differences in average snowmelt runoff between these two sites during 2007-2011 (Fig. 6).

Hence the results of Paper II indicate that stream responses to snowmelt are highly variable in both, disturbed and undisturbed boreal forests and that the specific mechanisms controlling spring snowmelt are more important than the impact of forest removal. These mechanisms include (i) interception of snow in the forest canopy, reducing SWE; (ii) sublimation directly from the snowpack; and iii) additional losses of melt water by evaporation or GW recharge during the melt.

The more important hydrological effect of clear-cutting in the Balsjö catchment was therefore attributed to changes of the water balance during the summer. Annual runoff of the CC-4 and the NR-7 catchment during the hydrological years of 2007-2011were quantified as 487 mm and 298 mm in the CC-4 and the NR-7 catchment, respectively (Fig. 6). This is in good agreement with the literature (Bosch & Hewlett, 1982; Troendle & King, 1985; Hornbeck *et al.*, 1993; Andréassian, 2004; Brown *et al.*, 2005), were for example the classical review article by Bosch & Hewlett gives estimates of ~40 mm increase in runoff per percent harvested catchment area for coniferus and eucalipt forests. Applying these values for Balsjö would result in an expected difference of ~260 mm, which is more than the observed difference of 189 mm between the two catchments. However, such these discrepancies may be caused by the shorter growing season in Balsjö (150-180 days; Löfgren *et al.*, 2009) compared to most of the studies included in Bosch & Hewlett's review study. In turn, this underlines the need to further quantify hydrological effects in paired catchment studies of high altitude regions (Buttle *et al.*, 2000).

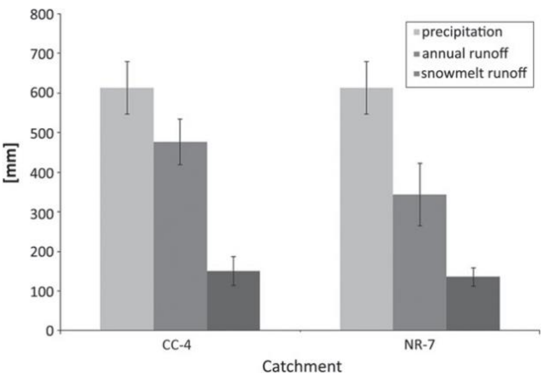

Figure 6. Water balance during the hydrological year of CC-4 clear-cut, as well as the NR-7 reference catchment, respectively (from Paper II). 'Annual runoff' represents average discharge after harvest for the years 2007-2011. 'Snow melt' is the average sum of all runoff that discharged during the snow melt period. Precipitation data represents sums (hydrological year) of daily open field precipitation between 2004 and 2011. Error bars indicate standard deviations.

3.3 Drivers of Increased DOC Concentrations

In Paper III the effects of various drivers on stream DOC concentrations were evaluated. The results of the performed regression models and the PCA clearly indicated that shallow GW levels are the first-order mechanism for DOC mobilization in the Balsjö catchments. This is in agreement with other studies that have investigated the temporal dynamics of DOC mobilization (Bishop *et al.*, 2004; Grabs *et al.*, 2012; Xu *et al.*, 2012).

Further, clear-cutting was found to increase soil temperatures during summer with up to 5° C higher values at 50 cm soil depth in the clear-cut compared to the reference slope in August – a pattern that has been observed elsewhere (Olchev *et al.*, 2009). At the same time, higher soil moisture levels were sustained in the clear-cut soils during the growing season.

To identify the role of these changing soil conditions on DOC mobilization, the effect of changing flow pathways was modeled using the RIM model. Modeled changes in flow-pathways using RIM were able to explain a major part of variation in stream DOC concentrations during the pre-treatment period (r^2= 0.4-0.7), but the model performed less well after the harvest. In an additional step, the post-harvest model residuals were compared to the changes in soil temperatures and soil moisture. But whereas no linear dependence of model residuals to soil moisture changes was found, model residuals were highly sensitive to changes in soil temperature (Fig. 7).

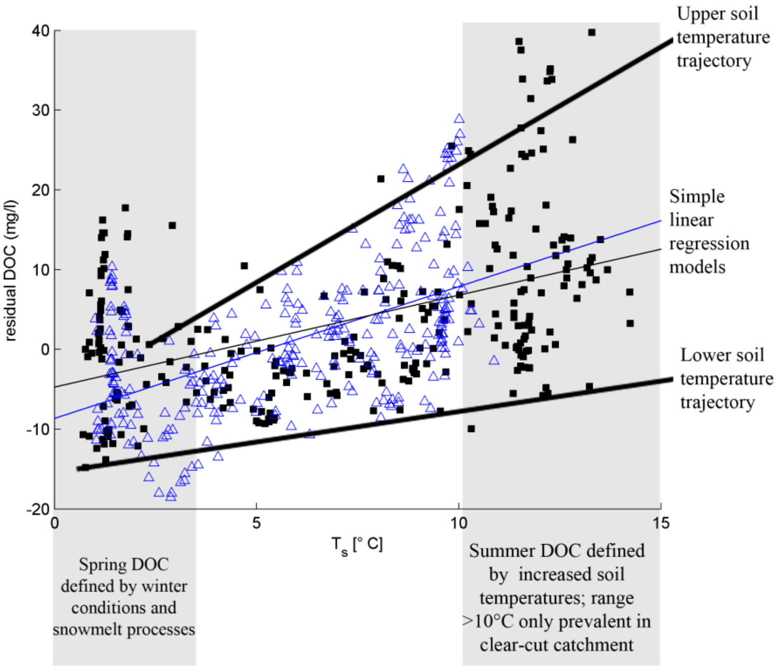

Figure 7. Conceptual model of the 2nd order control of DOC in stream water as represented by the sensitivity of DOC residuals (modeled-measured) using static-RIM to evaluate the effects of DOC on flow-pathways to soil temperature (T_s) at 50cm soil depth. Whereas spring time DOC concentrations were found to be controlled by various winter and spring processes, summer and fall DOC was highly sensitive to increasing soil temperatures within a range indicated by the upper/and lower soil temperature trajectories. Equations for linear regression models are given in Paper III, Figure 6.

This relationship was confirmed by linear regression models for the temperature dependence of DOC concentrations in soils. These models were not different in the disturbed and undisturbed catchments, indicating the linear dependence of mobile DOC in the soil solution on soil temperature (Fig. 7).

These results are in agreement with earlier studies that have hypothesized a soil temperature control on DOC availability (Hornberger *et al.*, 1994; Boyer *et al.*, 1997; Tipping *et al.*, 1999) and research from Sweden, in which strong seasonal patterns in DOC concentrations were found (Köhler *et al.*, 2009; Seibert *et al.*, 2009). Furthermore, these seasonal variations were recently linked to variations in soil temperature which was identified to act as a second order control on stream DOC concentrations (Winterdahl *et al.*, 2011a). Overall these results suggest that the increased DOC mobilization after forest disturbance originated from catchment soils that responded to the changing environmental conditions, but that the overall DOC mobilization mechanisms have remained the same as in the undisturbed catchment.

Among the interesting questions arising from Paper III is why the temperature related increase in DOC availability in soils, often conceptualized as a temperature dependent DOC production (Futter *et al.*, 2007; Svensson *et al.*, 2008) is not paralleled (and therefore compensated) by an increased C-mineralization (Kirschbaum, 1995; Mallik & Hu, 1997; Conant *et al.*, 2011). Such a mechanism has been hypothesized to account for increased leaching of DOC in temperate forest soils (Bengtson & Bengtsson, 2007). In Paper III we suggest that the temperature dependencies of soil DOC production and C-mineralization are different. Thus the increase in DOC production may be larger than the increase in DOC mineralization. The surplus of the soil DOC pool would then be available for the increased DOC mobilization into streams and consequently increase DOC concentrations in streams during summer.

Overall these results highlight the sensitivity of boreal first-order streams to changes in the energy and water balance, respectively, which may be altered as a result of both, extensive land management and climate change.

3.4 Downstream Transport of DOC in a Stream Network

In paper IV the downstream effects of the increased DOC inputs from harvested areas were evaluated. The mixing model used in this study was able to simulate the measured DOC concentrations well at the smaller, 8.7 km^2 catchment located upstream of a larger wetland area. The good agreement of measured and modeled concentrations at this site (Regression: $DOC_{modeled} = 0.84^* DOC_{measured} + 2.0$; $r^2=0.97$; $p<0.001$) indicated that enhanced discharge and increased DOC concentrations from harvested areas are important for downstream sites. Hence, any upstream alteration in hydrology and/or DOC concentration can directly affect DOC concentrations downstream. The results generally follow existing literature showing the large effects of upstream contributions of DOC source areas for downstream sites (Schiff *et al.*, 1998; Laudon *et al.*, 2004; Temnerud *et al.*, 2007).

Larger differences between modeled and measured DOC concentrations were found for the larger 22.9 km^2 ha catchment located downstream of the wetland, in which the percentage of harvested area was smaller. Similar differences between upland contributions and the outlets of larger meso-scale streams have been shown in a similar stream network in the region (Laudon *et al.*, 2011a). Among the hypothesized mechanisms for these differences is the dilution of DOC rich runoff from small sub-catchments with deeper GW that is low in DOC (Schiff *et al.*, 1998). Alternatively, the longer residence time of DOC during transport within the stream network, in which open water bodies are also prevalent, could provide an environment for additional DOC processing. Shallow ponds have for instance been shown to act as bioreactors that can modify the DOC signal in terms of both, DOC concentrations and DOC quality (Tranvik & Bertilsson, 2001; Schelker *et al.*, 2011; Ask *et al.*, 2012; Burns *et al.*, 2013).

Furthermore, the modeling results of Paper IV also provided estimates of the critical area ($A_{critical}$), the area needed to be clear-cut harvested to cause a significant effect on downstream DOC concentrations. Significant increases in DOC concentrations ($p<0.05$) at the downstream sites were found, if $A_{critical}$ exceeded 11% of the catchment area. Highly significant increases ($p<0.001$) could be determined when more than 23-25% of the catchment area was clear-cut. These results suggest that harvests that are larger than $A_{critical}$ will affect downstream DOC concentrations in a meso-scale boreal stream.

However, even though a non-significant result does not mean that there is no treatment effect (see e.g. Bosch & Hewlett (1982) for a similar discussion on the suggested threshold of 20% harvest in paired catchment studies that is required to cause a ‘detectable’ hydrological effect), the fact that DOC concentrations above $A_{critical}$ are significantly higher than the natural variation suggests that ecological implications for sensitive boreal stream networks are likely (Bridcut *et al.*, 2004; Laudon & Buffam, 2008; Serrano *et al.*, 2008). The outcomes of Paper IV suggest therefore that the estimates of $A_{critical}$ could be used in boreal rivers to provide a harvesting-threshold to be included in practical forest planning.

4 Conclusions and Final Remarks

In Papers I-IV it was concluded that:

- DOC concentrations in boreal first-order catchments are observed to increase as a response to forestry operations (Paper I)

- The hydrological effects of forest removal are affecting snow accumulation and melt, but the major impact on the water balance is given during summer, when evapotranspiration controls the water balance (Paper II)

- Riverine C-exports can be enhanced by clear-cutting. The fluxes are then representing an important fraction of the C-balance of a boreal forest ecosystem (Paper I)

- The major drivers of the increased DOC concentrations in first-order streams are i) changing flow-pathways that activate more surficial soil layers through increased GW levels and ii) higher soil temperatures that increase the DOC availability in soils (Paper III)

- Increased DOC inputs combined with increased discharge from harvested sub-catchments contribute to DOC concentrations at downstream sites. However, this signal may be modified by additional landscape features, such as lakes and ponds (Paper IV).

- Forest management of sensitive boreal catchments could be optimized towards better water quality by limiting the total harvest area within a larger stream network to 11-25% of the catchment area (Paper IV).

Among the fundamental questions arising from these results is whether they can be transferred to other, similar catchments. But whereas a direct answer to this question is difficult to give without further empirical investigations in similar catchment-scale studies, a discussion of potential spatio-temporal limitations of the work performed within this thesis will give some indications.

First, it should be noted here that the spatial scale of the Balsjö paired catchment experiment is limited. This becomes especially evident, if the total area harvest within the BA-1 catchment is compared to the area that was clear-cut harvested in the county of Västerbotten (Fig. 8): Whereas the clear-cut area within BA-1 summed to 2.6 km^2 during 2002-2011, the total area that was clear-cut harvested was quantified as 2266 km^2 in the county of Västerbotten during the same years. The Balsjö experiment therefore only covered an area of approximately 0.1% of the harvests in the county.

A second limitation may be given by the timescale of the study. The results and conclusions drawn in this thesis are based on data that has been collected within less than one decade (2004-2011). Whereas this time frame may be sufficient to quantify the direct effects of clear-cutting on stream chemistry (also termed *'short-term effects'*; see Löfgren *et al.*, 2009), the Balsjö experiment is limited in answering questions on how long the effects of clear-cutting on water quality will persist and when a full recovery can be expected.

Furthermore, the results of this study were based on the assumption of an '*equal response*' within the pre-treatment period in the paired watershed design (Hewlett, 1971; Andréassian, 2004). The short pre-treatment period in Balsjö of two years (spring 2004 until spring 2006) may therefore be criticized. Short pre-treatment periods of only one to two years, respectively, have also been questioned in the literature (Buttle *et al.*, 2005)[2]. However, this limitation may be difficult to overcome, if paired catchment experiments are initiated within projects that depend on short and intermediate funding. Conversely, boreal sites that are included in long term monitoring programs and that are supported by long term funding (such as the nearby Krycklan-Svarberget LTER site; Laudon *et al.*, 2011a) are commonly not subject to similarly intensive land management and do therefore not allow to directly investigate the impact of land use with primary data.

Another important question arising from this discussion is whether forest disturbances by forestry operations can be discriminated from other, natural ecosystem disturbances. As in other boreal forests, natural disturbances in boreal regions of Scandinavia consist of forest fires, wind through, and insect infestations that are reoccurring with varying frequencies (see e.g. Wardle *et al.*, 2012 for examples of varying fire frequencies) and these natural disturbances may also have pronounced effects on stream water quality (Carignan & Steedman, 2000; Lamontagne *et al.*, 2000). Overall this aspect has

2. It should be noted that this study was published after the Balsjö experiment was initiated.

only been briefly touched upon in the papers included in this thesis (i.e. by referencing to the ongoing discussion on forest disturbance and flood frequencies in Paper II; see also Alila *et al.*, 2009; Kuraś *et al.*, 2012). However, the effects of other, naturally occurring forest disturbances on water quality may need further investigations. Furthermore, the question if frequencies of these natural disturbances have changed as a result of human impact (e.g. as a result of climate change) and, in turn, exert additional pressure on stream water quality remain beyond the interpretability of the results of this thesis.

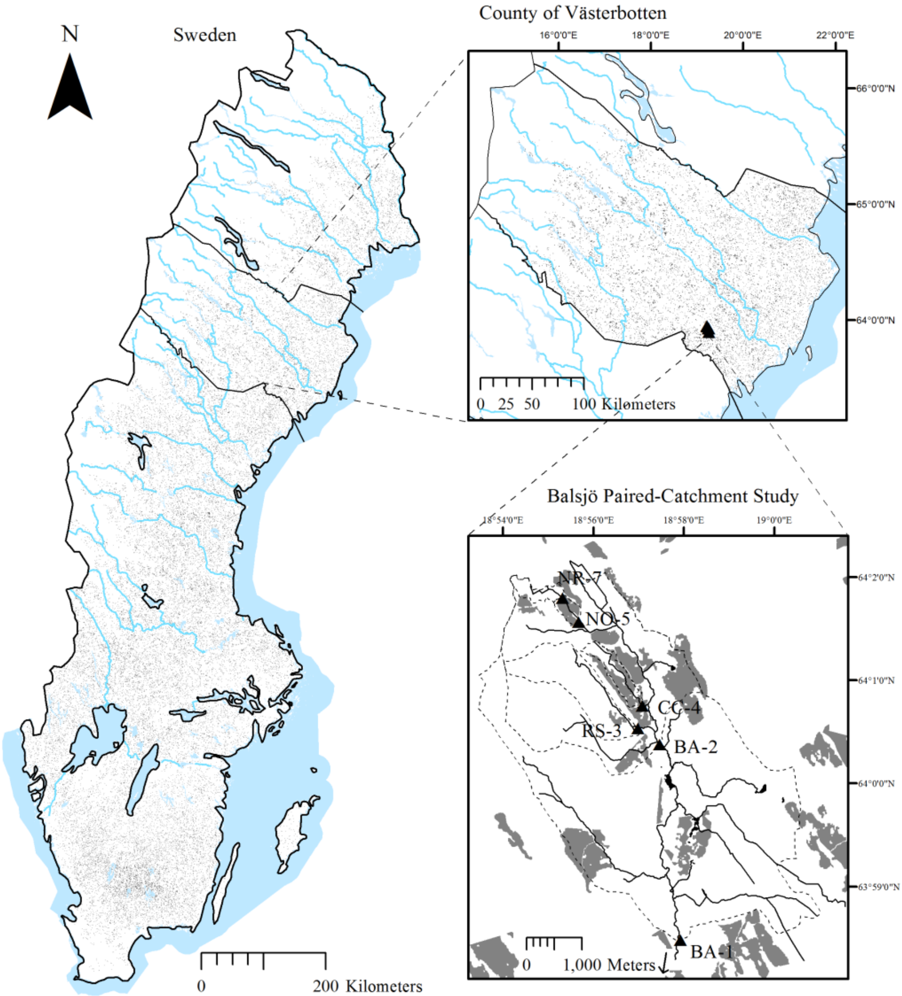

Figure 8. Final-fellings in Swedish forests performed between 2001-2011. Map of Sweden (left), county of Västerbotten (right, upper) and the Balsjö paired catchment Study (right, lower). Final-fellings are derived from satellite images (see Paper IV for a full description of this Method) and are marked grey in all three maps.

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