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The effects of Forest clear-cutting on Stream water DOC

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This report presents an MSc thesis at the Department of Forest Ecology and Management, Faculty of Forest Sciences, SLU. The work has been supervised and reviewed by the supervisor, and been approved by the examinator. However, the author is the sole responsible for the content.

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ABSTRACT

Dissolved organic carbon (DOC) is a dominant feature of water chemistry that strongly influences pH, buffering capacity, nutrient concentrations and bioavailability of metals and organic pollutants.

This study of DOC concentrations in stream water was performed North West of Balsjö in northern Sweden. Sampling was performed during spring flood that is the prevailing hydrological period of the year. One watershed was totally clear-cut all the way to the stream, another was clear-cut leaving buffer strips along the stream channel, while a third catchment was left as a control. The treated areas were compared with the control area considering flux and concentrations of stream water DOC. The treated areas were also compared to a pre treatment period pervious year. The main objective of the study was to examine if the flux and concentration of DOC was affected by clear felling during spring flood in this northern part of Sweden. The second aim of the study was to investigate if a buffer strip reduced the amount of DOC in stream water.

Results of the study shows that clear cutting significantly increased the concentrations of dissolved organic carbon and output loads in run off water in the Balsjö forest catchments during the first year after clearing. The clearing also resulted in a higher runoff during spring flood. Considering the effects of a buffer strip, the result is rather speculative due to the study setup but indicates that a buffer zone might reduce transportation of DOC to water courses.

SAMMANFATTNING

Löst organiskt kol,(på engelska: dissolved organic carbon, DOC) har stor påverkan på vattenkemin. DOC förändrar bl.a. vattendragens pH, buffertkapacitet, näringskoncentration samt metallers och organiska föroreningars biotillgänglighet.

En studie på skogsbruktes påverkan på DOC koncentrationen i strömmande vatten utfördes nordväst om Balsjö i Västerbotten. Tre avrinningsområden studerades, ett som kalhöggs ända fram till bäcken, ett där man sparat en buffertzon längs bäcken samt ett som lämnats som kontrollområde. Vattenprover togs under vårfloden (april-maj) med hjälp av en automatisk provtagare. De tre områdena jämfördes med avseende på DOC-koncentration och flöde, dels med var andra men även med uppmätta värden från föregående år innan avverkning ägt rum. Syftet med studien var att undersöka hur flöde och koncentration av DOC i vattendragen påverkas av kalavverkning i denna del av landet samt om en buffertzon minskar transporten av DOC från skogsmark till vattendrag.

Resultaten visar att i de studerade avrinningsområdena ökar kalavverkning märkbart den uttransporterade mängden och koncentrationen av löst organiskt kol under det första året efter avverkning. Kalavverkning resulterade även i en högre avrinning under vårfloden. Buffertzonen verkar reducera uttransporten av DOC till vattendragen men på grund av studiens upplägg går det ej att dra några säkra slutsatser om buffertzonens effekt.

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INTRODUCTION

In year 2000 a new law was attained by the European Union, the EU Water Framework Directive (RDV, 2000/60 EG). The aim of the directive is to attain good ecological and chemical quality of all surface and ground waters in Europe before year 2015. According to the directive, water quality and biological activity is only allowed to deviate marginally from the natural condition.

Since forestry is the major land use in Sweden and cover large areas it has an important role in the work for reaching the goal of the directive. It is well known that forestry affect water quality (Cummins and Farell, 2003) and minimising the pressures from forestry is a key to ensure that that forest water bodies achieve good water status by 2015. To solve the problem with continued forestry and improved water quality, research and monitoring of forest water systems has to be performed to evaluate how forest pressures can be effectively minimised and how forestry can contribute to improve the quality of waters.

The common way to diminish forestry impact on water is to leave buffer strips along lakes and watercourses that limit incoming light, equalize water temperature, supply organic material, even out flow, prevent erosion and capture nutrients before reaching the surface water.

One substance of special interest in many regions is dissolved organic carbon (DOC). DOC is an important energy source for aquatic organisms (Hobbie 1992, Moran and Hodson 1990) and affects biological activities by limiting light penetration in surface waters (Moore 1989). DOC is also a dominant feature of the water chemistry that strongly influences pH, water buffering capacity, nutrient concentrations, and bioavailability/toxicity of metals and organic pollutants (Temnerud and Bishop 2005). Several studies have found that an increase in dissolved organic matter (DOM) enhance the mobility and solubility of trace metals and contaminants because of the complexation capacity of organic material (Weng et. al. 2002, Tipping 2005).

Clear-cutting results in an increase in groundwater level and hence increase the run-off to streams by surface and near surface pathways which results in an increased transportation of DOC and nutrients (Rosén et a 1996, Cummins and Farell 2003, Porvari et al, 2003, Nieminen 2004).

In northern Sweden, close to Balsjö in Västerbotten, a study was started in 2004 to examine the hydrological response of different forestry methods. During 2005 the naturally forested study catchments were compared to investigate if there were any pre-treatment differences. In the winter of 2006, one watershed was totally clear-cut all the way to the stream, another was clear-cut leaving buffer strips along the stream channel, while a third catchment was left as a control. In this study, the two treated areas will be compared with the control area considering flux and concentration of dissolved organic carbon (DOC).

The hypothesis of this study was that the hydrology decides DOC concentrations in stream water and that clear-cutting gives an increased and more rapid snowmelt. As a result of those higher flows, more shallow flow paths are activated were the amount of organic carbon is higher, which in turn increases the concentration of stream water DOC during spring flood. The main objective of this study was therefore to examine if the flux and concentration of DOC was affected by clear felling during the spring flood in this northern part of Sweden. The second aim of the study was to investigate if a buffer strip reduces the amount of DOC in stream water.

BACKGROUND

DOC

Dissolved organic carbon (DOC) is defined as the fraction of organic carbon that passes through a 45µm filter. The carbon can come from in-stream processes such as leachate from dead aquatic organisms, then called autochthonous, or from leachate from surrounding soils and inputs from riparian trees called allochthonous.

The acid functional group ($RCOO^-$) of DOC is an important supplier of H^+ in stream water during the spring melt events and high levels of DOC can decline pH up to two units by increasing the H+ concentrations (Laudon et al 2000).

Contaminants sorbed by colloids like DOC are less toxic than free contaminants since bioavailability is significantly reduced after sorption. The sorbed contaminants are transported with DOC from the forest floor to streams and lakes where a change of conditions e.g., pH may be all it takes to release it in the more toxic form as free ions. This can be illustrated by aluminium (Al) in the following reaction where X is an organic ligand and n is the number of hydrogen ions that exchanges for every Al in the complex. During acid conditions the reaction goes to the left, which releases more soluble, toxic aluminium as Al^{3+} (Berggren and Mulder 1995)

$$AlX^{(3-n)} + nH^{+} \leftrightarrow H_n\,X + Al^{3+} \qquad (1)$$

Studies have shown that aluminium concentrations in stream water are closely related to DOC and that humic substances are an effective agent for the complexation of Al in the soils (Denning et al 1991, Grieve and Marsden 2001, Cummins and Farrell 2003).

Mercury (Hg) has similar behaviour and has been assimilated for many years in forest soils where it binds strongly to organic matter. That binding is so strong that the transport of mercury to water courses is dominated by the transport of organic material (Shanley et al 2002, Porvari et al 2003, Skyllberg et al 2003)

Spring flood

Since the region is snow covered for 6-7 months of the year, the snowmelt period is the prevailing hydrological period in the region where 25-60% of the annual runoff occurs within just a few weeks during spring flood (Bishop and Pettersson 1996). That makes the period very important for understanding the export from forested areas of both nutrients and organic materials. Studies have shown that 50% to 68% of annual export of total organic carbon (TOC) occurred during the one month long spring flood period (Laudon et al 2004). Snow pack accumulates contaminants of many months that flush through the system in a relatively short period in the spring and early summer. Spring time is also the time when many species are in their most sensitive life stage.

A study in North America, found that pH and acid neutralizing capacity (ANC) in surface waters were much higher than observed in melt water collected from the of the snowpack (Denning et al. 1991). This indicates that water from forest soils moderated the inputs of strong acidity from the snow pack, preventing surface water acidification. Studies have also demonstrated that during spring flood, a new source of total organic carbon (TOC; often analogues to DOC) is activated by the superficial flow that occurs at high melting rates (Bishop et al. 2004). The surface layers are rich in organic material and during spring flood they could have a direct flow path to the stream due to a rise of the water table. The superficial flow increases the TOC concentrations in run-off even though other substances are diluted (Bishop et al. 2004). Bishop et al. (2004) showed that concentrations of TOC decreased with depth in opposition to Ca^{2+} which increased with soil depth. At low flow periods, water infiltrate deeper into the mineral soil where sorption and degradation of organic material is higher resulting in lower TOC concentrations (Cronan and Aiken 1985, Bishop 1996). The decline in TOC concentrations after the initial increase in stream water during spring flood is thought to result from a depletion of this newly activated source areas (Laudon et al. 2000). Denning et al. (1991) showed that there is a flush of nutrients in the beginning of the snowmelt that supports the idea of soil solution flushed into the streams. The author suggests that organic decomposition proceed slowly under the snow pack throughout the winter resulting in an accumulation of decomposed products in the soil solution.

Impacts of forestry

In addition to the water framework directive, the Swedish Parliament has adopted 16 environmental quality objectives (Miljömålsportalen, 2008). The objectives define the state of environment and provide a coherent framework for environmental programmes and initiatives at national, regional and local level. One of the objects is “Sustainable forests” with the aim that the value of forests and forest land for biological production must be protected, at the same time as biological diversity and cultural heritage and recreational assets are safeguarded. The objective is intended to be achieved within one generation. According to the government the objective includes that the forests' natural hydrology is protected.

Forests cover half of Sweden and forestry is one of the country’s most important industries. Several studies have shown that clear-cutting result in an increase in runoff (Rosén 1984, Rosén et al 1996, Andréassian, 2004) and that snow pack accumulation is higher in clear-cut areas than underneath the forest canopy where much of the precipitation never reaches the ground due to evaporation from the branches (Bhatti et al 2000, Murray and Buttle 2003). Murray and Buttle’s (2003) study also showed that daily melt rates tend to be greater at clear-cut areas than in the forest. The result of this is a less efficient infiltration of snowmelt water at the clearing than in the mature forest. That increases the runoff to streams by surface and near surface pathways which results in an increased transportation of DOC with associated heavy metals and nutrients to the stream (Rosen et a 1996, Cummins and Farell 2003, Porvari et al, 2003, Skyllberg et al, 2003, Nieminen 2004).

Woody debris at the clear cut area will after a while be decomposed and the organic matter that already is in the soil before clearing may also be subject to increased mineralization as a result of changes in soil moisture conditions, temperature and the enhancement of nutrient cycling after harvesting. This could result in an even higher loss of DOC to watersheds after a few years (Porvari et al 2003, Kalbitz et al 2004).

Buffer strips

The general way to diminish forestry impact on water is to leave buffer strips along lakes and watercourses. Common buffer width along small streams in Sweden, if any, is 10 m (Anon. 2002) .The contact between land and water creates unique conditions for a wide range of terrestrial and aquatic organisms. It is well known that buffer strips have a major influence on biodiversity (Hyllander et al. 2002, 2005). Preserving buffer strips have also a positive influence on water quality in out-streaming water from forest soils by limiting the export of particles. That requires however that here are no vehicle tracks or ditches through the buffer strips since the buffer zones which can provide overland flow directly into the adjacent stream (Nyberg and Eriksson 2001). Buffer strips have also been seen to decline export of nutrients released by clear cutting (Ahtiainen 1992). Improved water quality in turn improves the biodiversity of life in water courses. Swedish legislation is very vague regarding buffer strip management. It only states that buffer strips should be retained to the extent that is needed with respect to values of plants, animals, culture and the landscape (Anon. 1993).

METHODOLOGY

Study area

The study was conducted in two watersheds, Balån North and Balån South (64º02´N, 18º57´E) situated about 13 km NW of Balsjö in northern Sweden, see figure 3.1. The north area is divided in two parts (fig. 3.2) were Balån 6 is left as a control area and Balån 5 is clear-cut with a forested buffer zone left along the stream. The buffer strip is approximately 5 m wide. The south area, Balån 4, is clear-cut down to the stream. Harvesting started in March 2006 and was performed mechanically according to silvicultural practices typical of this area, leaving branches and tops on site. An exception is the forested buffer zone along the stream at Balån 5, which is usually not left at a water-coarse of that small size.

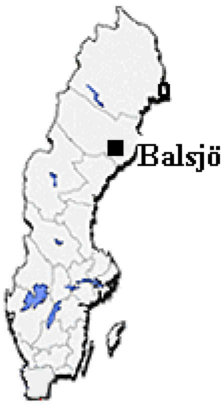

Fig. 3.1. Balsjö study area in northern Sweden.

Cartographer Christer Eriksson, estimated the size of the catchments at Balån 6 to 19,8 hectares, Balån 5 to 11,4 hectares and Balån 4 to 36,5 hectares. The catchments were vegetated by coniferous forest, in low-lying, wetter areas mainly Norway spruce (*Picea abies*) and at higher better-drained areas Scots pine (*Pinus Sylvestris*). Podzol soils are the most common soil type in the catchments, with organic rich soils in the riparian near stream zones. The area has been ditched during the first half of the 20th century to improve the conditions for forestry. At the same time the streams have most likely been straightened which was a common practice by local farmers. The annual air temperature in the area is about 0.6 °C and the annual precipitation is about 554 mm (Ring and Högbom 2005).

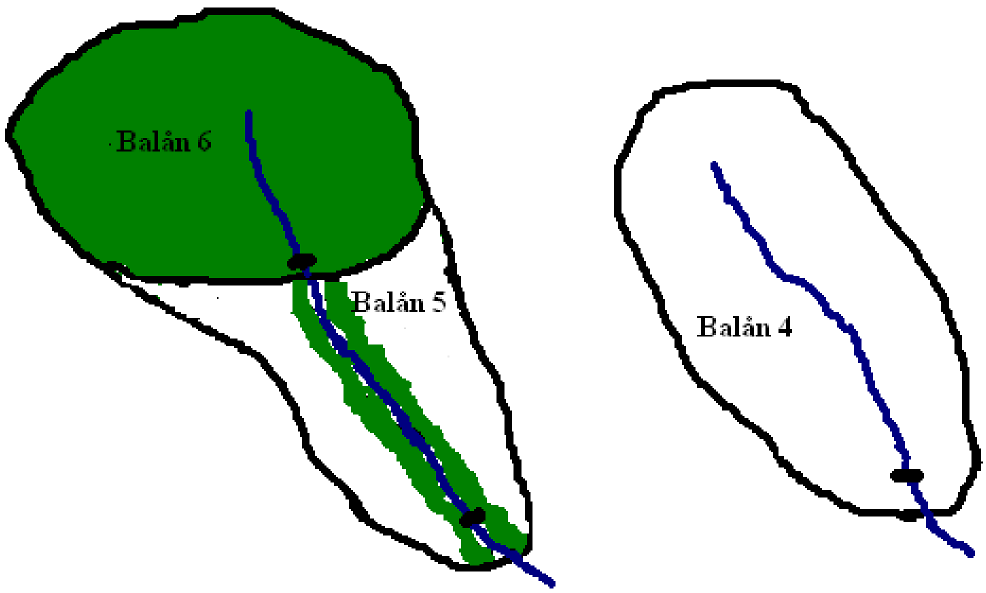

Fig 3.2. Schematic map of the catchments in Balsjö with the weirs marked as black dots and intact forest marked in green.

Sampling procedure

To ease the flow measurements V-notch weirs were built at the outflow of the catchment of the three study areas (fig 3.2). At each weir water level was measured on an hourly basis by two TruTrack Water Height Loggers WT-HR. In 2006 ISCO pump stations were placed at the weirs (fig 3.2) that automatically took samples every sixth hour from the stream runoff. At the recession limb of the hydrograph the sampling interval was decreased, first to every twelfth hour and finally to once a day when close to base flow. Sampling was performed during spring flood, 12 April to 24 May 2006, when DOC flux was expected to be greatest to provide the best opportunity to identify the extent of the DOC export.

Water analysis

Samples were kept dark and cool in time between sampling and analysis. Analysis was performed at the Swedish University of Agricultural Sciences, Department of Forest Ecology. Water samples for absorbance analysis were filtered using 0,45µm MCE membrane filters to remove particulate organic carbon and then measured at 254 nm in a 1 cm^3 quartz cuvette using a Perkin and Elmer spectrophotometer. Multiplied with 23,5 the absorbance correlates well with DOC for streams in this region (Laudon et al. 2004). During 2005 samples were taken approximately once a week and daily concentrations of DOC was interpolated from those weekly samples. At 2006 samples were taken several times a day and a mean values were calculated for each day. Measured and interpolated daily concentrations were multiplied by daily discharge to calculate daily loads. Discharge was calculated on an hourly basis from water level measurements.

RESULTS AND DISCUSSIONS

Discharge

Specific discharge (mm/day) during spring flow 2005 shows that the treatment areas are hydrological similar before clear-cutting (see figure 4.1). As shown in table 4.1, the total discharge during the spring flood period was 146 mm at the clear cut area while it was 157 mm at control area. That gives a ratio of 0,93 during the pre-treatment period indicating a marginal pre-treatment difference between the study catchments.

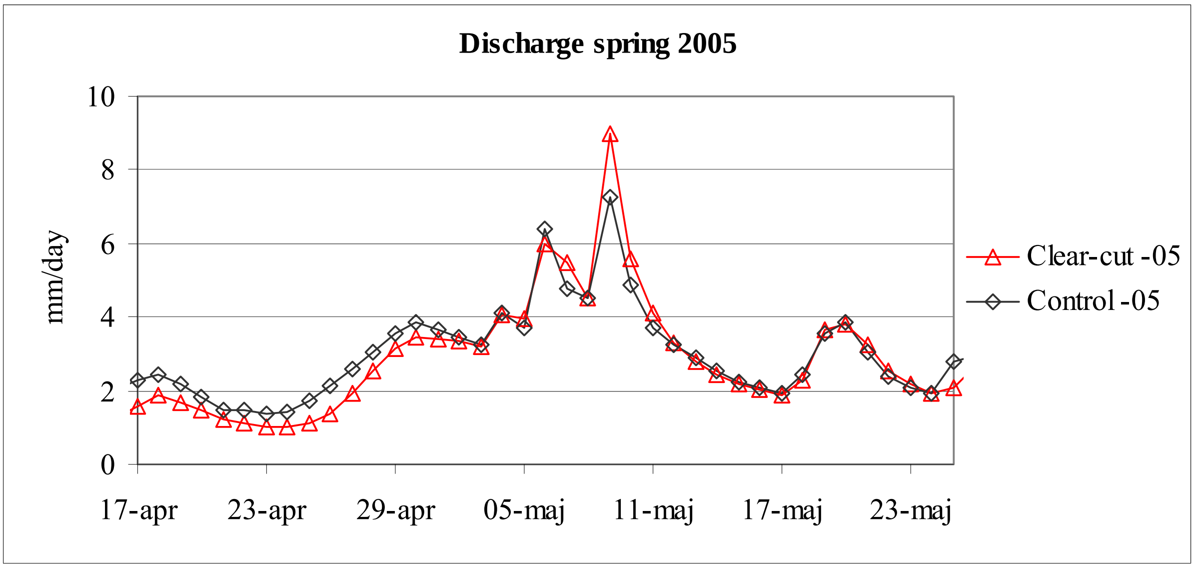

Figure 4.1 Discharge at clear-cut and control area measured pre-treatment.

After treatment, during spring 2006, the specific discharge during spring flow varies as shown in figure 4.2. As seen in the figure, specific discharge is higher at the clear-cut area than at the control area. After the clear-cut treatment the total discharge per unit area during the spring flood period was 161 mm at the treated area, and only 124 mm at the reference area giving a ratio of 1,29 between the two areas (see table 4.1). This increase in run-off is attributed to the clear-cut which has increased the flow during the spring flood by approximately 36%.

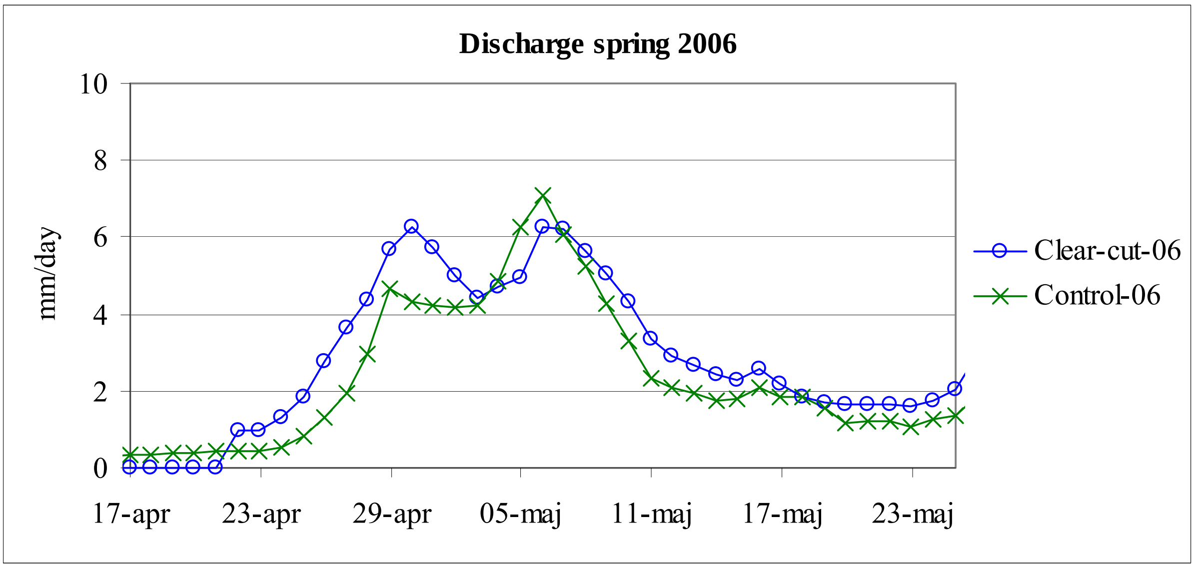

Figure 4.2 Discharge at clear-cut and control area measured past treatment.

In 2006, discharge at the control area has an initially smaller peak while the second peak is higher at the control area than at clear-cut area (fig 4.2). Throughout rest of the spring flood, the clear-cut area continues with a higher discharge than the control area. The higher total discharge during spring flood after clear-cut correlates well with both the hypothesis that clear-cutting results in higher flows and with earlier studies at other locations (Bhatti et al 2000, Murray and Buttle 2003, Rosen et al 1996, Cummins and Farrell 2003, Porvari et al 2003, Nieminen 2004). The higher discharge from the clear cut area indicates that there is a greater snow accumulation at the clear-cut area than in the forest at the control area. There is also a small indication of a more rapid snowmelt at the clear cut area indicated by the higher initial peak. An alternative explanation to the higher discharge after the clear-cut is that evapotranspiration, albeit small during the spring, is affected by the tree removal.

Table 4.1 Total output of water during spring flood at the research areas before and after treatment. Amount per unit area.

	Pre-treatment 2005	**Treatment 2006**
Control	158 mm	124 mm
Clear cut	146 mm	161 mm
Ratio	0,93	1,29

An error occurred at flow measurements at dam 5 so the buffer zone area is therefore excluded from the results including flow measurements. The error is probably due to uncertainty in measurements since there was only one working logger at the dam during some periods. The other two areas have a higher certainty in measurements since both loggers at the dams worked correctly. An additional explanation for the error could be the estimation of the catchment area by the cartographer since the water divide sometimes are difficult to interpret even in the field.

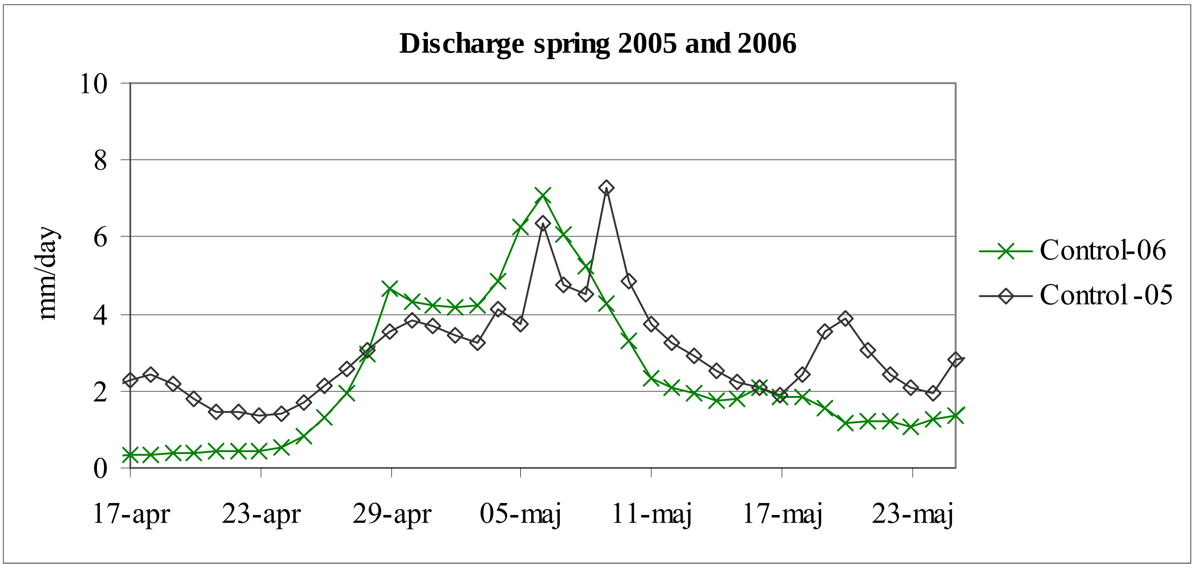

Figure 4.3 Discharge measured at the control area during spring 2005, pre-treatment and 2006, after the treatment.

A seen in figure 4.3 discharge patterns at the control areas were quite similar during the two years indicating that there were no major differences in discharge between the pre-treatment and treatment period.

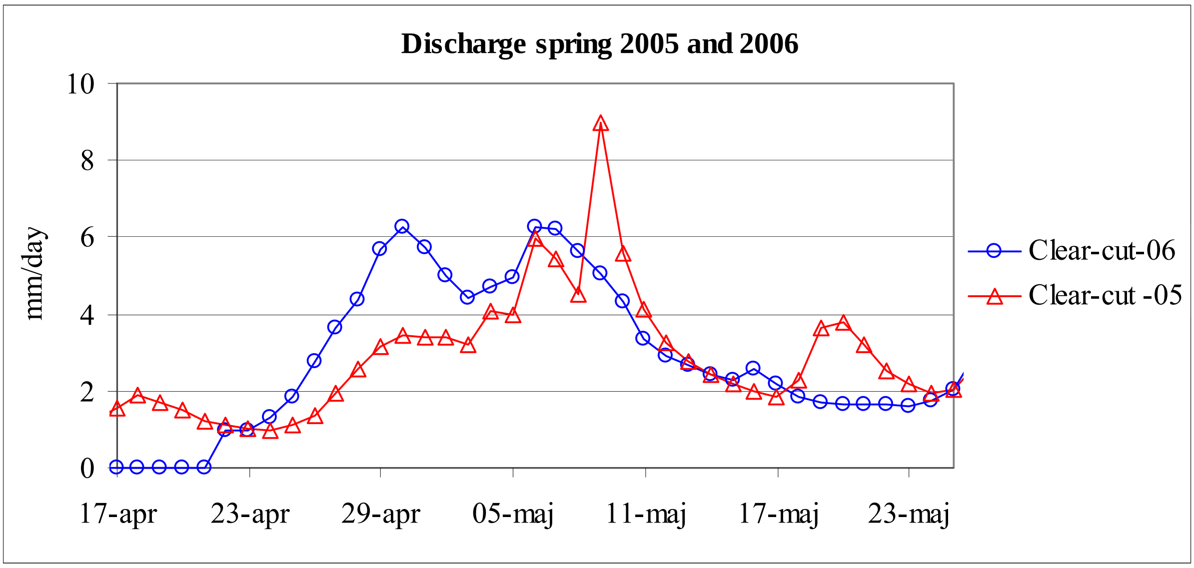

Figure 4.4 Discharge measured at the clear-cut area during spring 2005, pre-treatment and 2006, after the treatment.

After the treatment, the clear-cut area has an initial higher and more rapid discharge compared to the control area (figure 4.4). This initial higher discharge can not be seen at the reference area (see fig 4.3), indicating that the increase is a result of the clear-cut. A possible explanation to the higher initial discharge could be explained by higher day temperatures after deforestation due to solar radiation and lack of shadow resulting in an increased snowmelt. The high peak at the 8th of May 2005 can also be seen at the control area in 2005 indicating a change in temperature or rainfall.

DOC-concentrations

The concentrations of dissolved organic carbon in runoff water from the research areas varied between 8,6 and 35,8 mg/l. In 2005, the clear-cut area has a slightly higher DOC concentration than the other two study streams (figure 4.5). One-way ANOVA test showed however that the difference in DOC concentration between the three areas were not statistical significant (p=0.88).

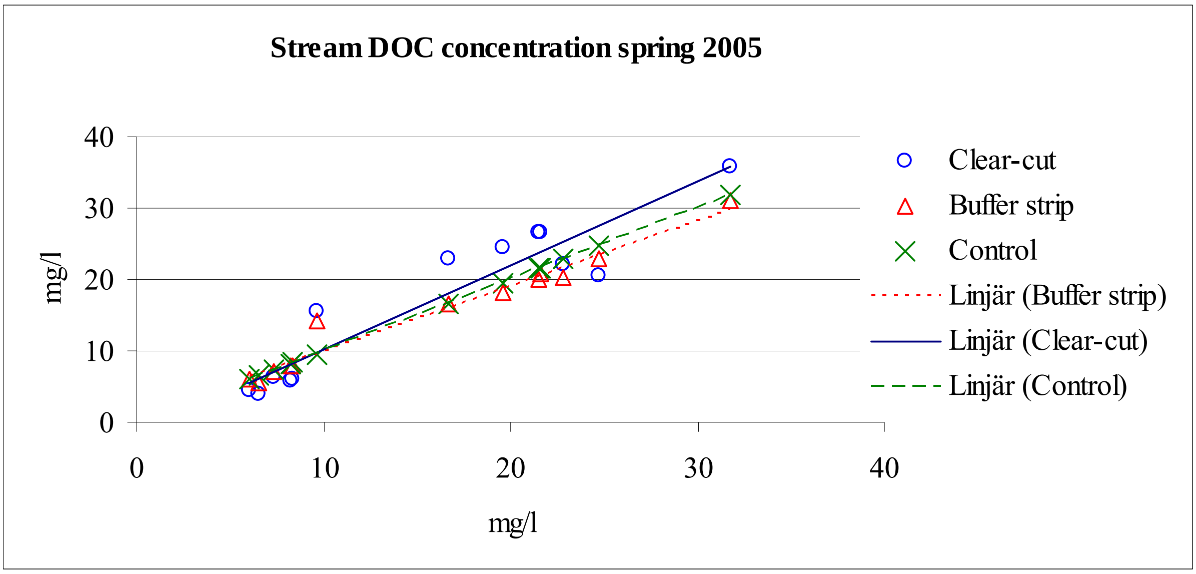

Fig. 4.5 Pre-treatment stream water DOC at the research areas.

In 2006, after treatment, the clear-cut area had higher DOC concentrations compared the other two areas (see figure 4.6). One-way ANOVA test showed that the clear-cut area differed significantly from both the control area ($p< 0.0001$) and from the buffer strip area ($p< 0,001$) The statistical test also showed that there were no significant difference between the buffer strip area and the reference area ($p=0.80$). This indicates that in this area, clear-cutting increased the concentrations of stream water DOC which are in good agreement with previous studies in boreal forests (Cummins and Farrell 2003, Nieminen 2004). The results also indicate that the buffer strip reduced the concentrations of stream DOC after felling compared to an area without buffer strips. Because the buffer zone and control catchments are nested, this result should be considered rather speculative.

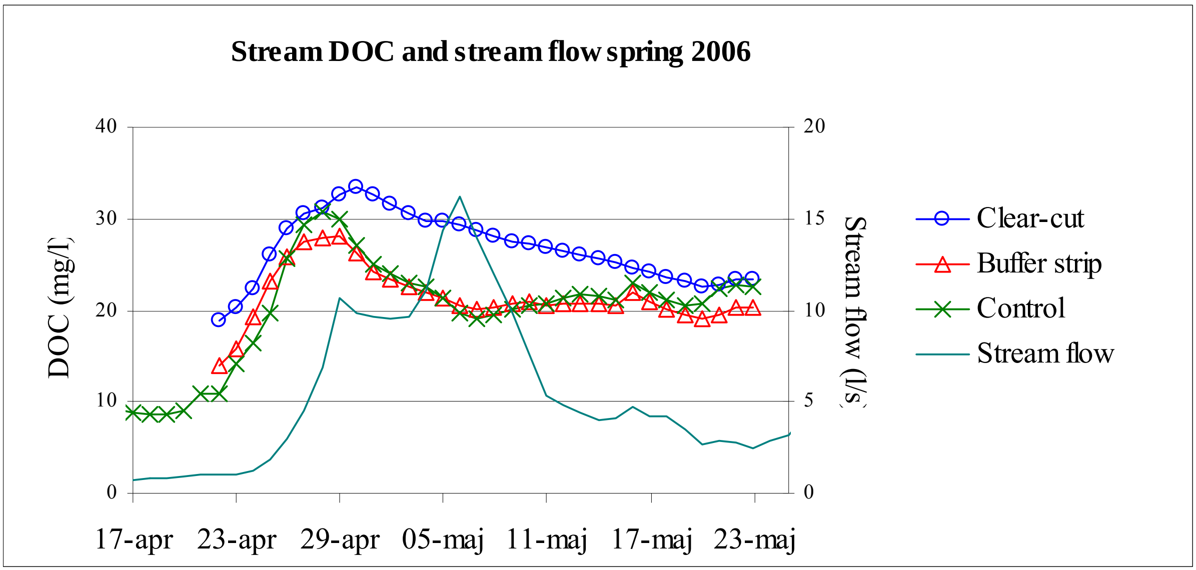

Fig. 4.6. Past treatment stream water DOC and stream flow at control area.

When DOC is measured at close intervals the pattern of DOC concentrations is more easily observed. In 2006, there was an initial steep increase in concentrations during the early part of spring flood followed by a gradual decline. This correlates well with the theory that during spring flood a new DOC source is activated during spring flood (Cronan and Aiken 1985, Bishop and Pettersson, 1996, Bishop et al 2004). The addition of relative little water, mobilize "old water" held in the unsaturated zone that becomes saturated as the ground water level rise and reaches highly conductive layers. At that point large volumes of water become suddenly released and reach the stream. The high DOC levels in spring flood water can be explained by the fact that stream chemistry primarily is determined by the riparian zone that is the last soil environment the water encounters before becoming surface water. In the riparian zone DOC concentrations is higher in the upper part of the soil horizon and declines with depth. As a consequence, the more superficial flow paths the higher will the DOC concentration in the stream become (Bishop et al 2004).

One of the main questions in this study was to investigate if clear-cutting contributes to an increased DOC export from watersheds in this part of Sweden. As seen in figure 4.7, the DOC export was a slightly higher from the clear-cut area than from the reference area during the pre-treatment period.

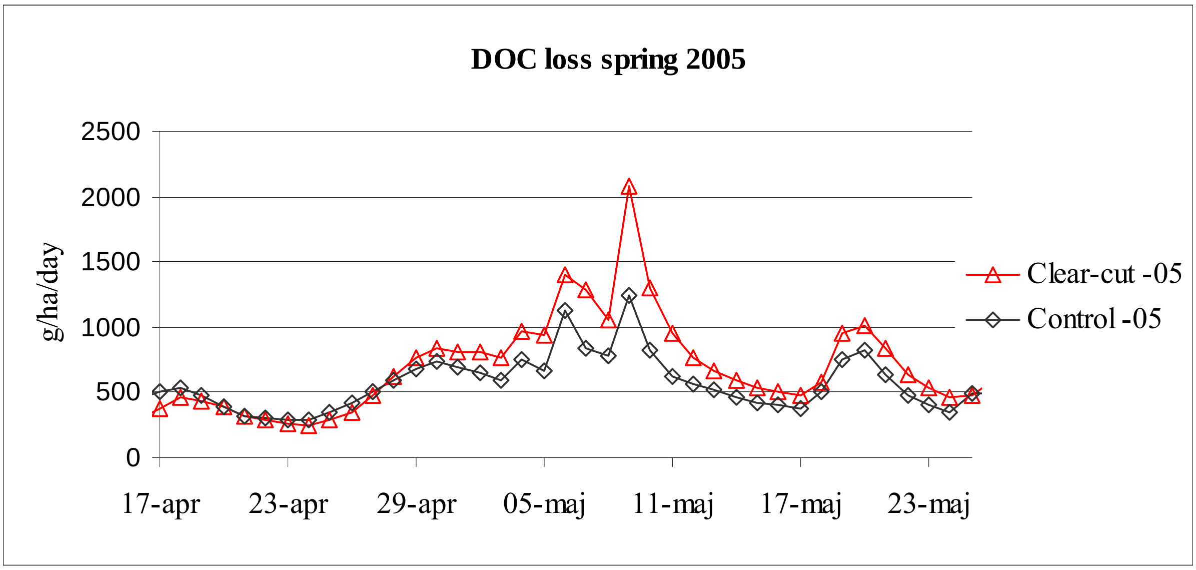

Figure 4.7 DOC loss in grams per hectare and day during the pre-treatment period at clear-cut and control areas.

The total DOC export during the pre-treatment period in the spring of 2005 was 35 kg ha^{-1} from the clear-cut area and 30 kg ha^{-1} from the control area giving a ratio of 1,17 (see table 4.2). After the clear-cut treatment, the export was 31 kg ha^{-1} from the clear-cut and 16 kg ha^{-1} from the reference area giving a ratio of 1.94. This suggests that the DOC export has risen substantially due to the clear-cutting.

Table 4.2 Total DOC export during spring flood from the research areas before and after treatment.

	Pre-treatment 2005	**Treatment 2006**
Control	30 kg ha-1 yr-1	16 kg ha-1 yr-1
Clear cut	35 kg ha-1 yr-1	31 kg ha-1 yr-1
Ratio	1,17	1,90

As shown in figure 4.8, after treatment, the DOC loss is much higher from the clear cut area in the beginning of the spring flood compared to the reference area where the export starts later. This might be a result of the earlier discharge at the clear-cut area seen in figure 4.2 A continued study will answer the question if the increased stream water DOC after clear cut continues following years as a result of an enhanced microbiological activity or if it is a one time phenomena as a consequence of the activation of the new DOC source in more superficial layers caused by an increased accumulation of snow in the clear-cut area. If it is the microbiological activity during winter the DOC export would be even greater the following year due to more organic material available for decomposition.

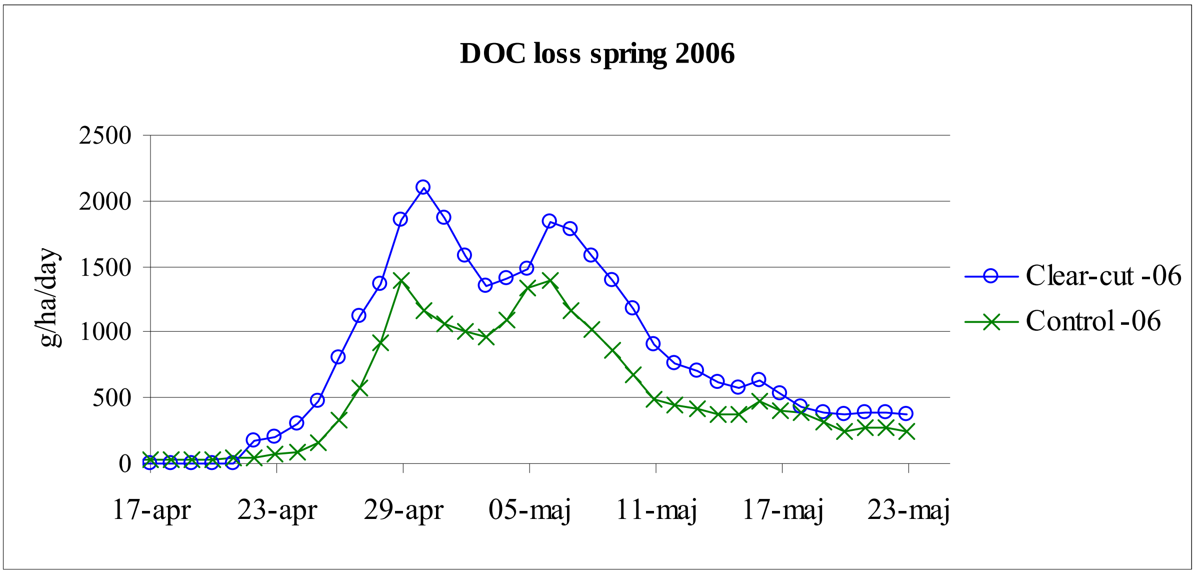

Figure 4.8 DOC loss in grams per hectare and day, after treatment at the clear-cut and control areas.

The mean daily DOC export during spring flood from the areas ranged from 0,40 to 0,96 kg ha^{-1} day^{-1} which is in agreement with an other study in the same region (Laudon et al 2004). The daily export increased from 0,57 to 0,96 kg ha^{-1} day^{-1}after clear-cut while export from the reference area was reduced from 0,49 to 0,40 kg ha^{-1} day^{-1}.

To get reliable values while monitoring spring flood it is important that samplings are performed at close intervals. As seen in figure 4.6, stream DOC concentrations rise quickly and if sampling is not carried out at intervals frequent enough, peak values can easily be missed giving misleading results. DOC concentration rises before flow and is thereby reaching its peak value before the peak in discharge. Sampling during spring 2005 was performed with approximately 10 days interval which is to rare to be sure not missing any peak values.

CONCLUSIONS

This study shows that clear-cutting significantly increased the concentrations of dissolved organic carbon and output loads in runoff water in the Balsjö forest catchment during the first year after clear-cut. The clearing also resulted in a higher run off during spring flood as a result of more precipitation reaching the ground. Since DOC is strongly connected with export and solubility of mercury, aluminium and other toxic metals higher concentrations of these elements in waters is thought be the result of clear-cutting.

The results of the study also indicate that a buffer strip could reduce the transport of DOC concentrations from forest soils to streams. Is seems like concentrations of DOC in the stream provided with a buffer strip does not rise as much after clearing as in the stream clear felled all the way to the waterside. Since flow measurement from the buffer strip area is not fully reliable the question need further investigation.

Since sustainability of forestry and the biodiversity of aquatic systems depend, among other things, on the input of organic matter and its related components keeping buffer strips along water courses could be a possible way of reaching the goals of both the EU Water Framework Directive and the Swedish national environmental quality objective “Sustainable forests”. To determine the effects of buffer strips on stream water quality, further studies are desired preceded by a more detailed and longer pre treatment period. Furthermore it is recommended with a study design where the control area is not nested with the treated areas since this has a possible influence on the results. Despite the unsuccessful study setup it would be of interest with a continued monitoring of the effects of clearing regarding total load of DOC from the watershed during the complete clear-cut period.

Improving and evaluating forestry methods is necessary with the ongoing intensifying of forestry that takes place today. The study showed that land management has a major role in controlling input of DOC and associated contaminants to aquatic systems.

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