Function and dynamics of woody debris in boreal forest streams

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Abstract

The work in this thesis deals with (1) the effects of woody debris on stream channel morphology and retention of organic material, and (2) the dynamics of woody debris and its relation to riparian forest history and composition. The studied stream reaches are situated in mature, productive forests in the boreal zone of Sweden.

Wood variables were important predictors of the frequency of debris dams, pool area, the proportion of pools formed by wood, and variation in the bankfull channel width. Pools formed by woody debris were mainly created by damming and had larger surface areas and residual depths than pools formed by other agents. Stream reaches intersecting old-growth forest (with minor influence of forest management) had coarser and longer woody debris pieces, greater amounts of wood, more debris dams, and wood-formed pools compared to streams surrounded by forests influenced by selective logging.

The influence of past forest management on the quality and quantity of woody debris in streams were analyzed by using dendrochronological methods. Selective loggings and absence of forest fires after 1831 resulted in lower input rates and a gradual replacement of pine by spruce over time. Residence times in stream channels of woody debris (>10 cm in basal diameter) were long and the oldest dated pieces of pine and spruce were over 300 and 100 years, respectively.

Dynamics of woody debris were explored by comparing wood volumes and characteristics between stream channels and their riparian forests and between old-growth and managed sites. Wood volumes recorded in the stream channels exceeded, but were related to, the volumes found in the riparian forests. Limited input of woody debris by bank cutting and absence of slope processes suggest that recruitment processes of woody debris to stream channels are similar as in riparian forests and slow decay in channels results in greater volumes.

The retentiveness of organic material in stream channels was examined by using release and capture experiments in multiple reaches during varying discharges using different sizes of leaf mimics. Sixty-eight percent of the variation in retention was explained by a multiple regression model including discharge and leaf mimic size. Between 44 and 80% of the variation in retention among reaches was explained by channel constraint, gravel coverage, and woody debris variables as the most important. Estimates from a partial least squares (PLS) model suggest an increase in mean transport distances by 22 to 53% in managed forest streams compared to old-growth conditions and in a low wood scenario, mean transport distances increased by 38 to 99% with larger increases for higher discharges and larger particle sizes.

To regain more pristine conditions of stream channels, management and restoration are needed to increase the amount of woody debris that recreates lost channel structures and increases the retention of organic material.

Key words: Boreal forest, CPOM, CWD, forest management, geomorphology, LWD, riparian forest, retention, residence time, streams, Sweden, woody debris

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List of Papers

This thesis is based on the following papers, which will be referred to by their respective Roman numerals.

I. Dahlström, N., and Nilsson, C. 2004. Influence of woody debris on channel structure in old-growth and managed forest streams in central Sweden. *Environmental Management* 33: 376-384.

II. Dahlström, N., Jönsson, K., and Nilsson, C. Long-term dynamics of large woody debris in a managed boreal forest stream. *Submitted manuscript.*

III. Dahlström, N., and Nilsson, C. Influence of channel characteristics on the retention of coarse particulate organic material in boreal, headwater streams. *Submitted manuscript*.

IV. Dahlström, N., and Nilsson, C. The dynamics of coarse woody debris in boreal regions are similar between stream channels and adjacent riparian forests. *Manuscript.*

Contents

Svensk sammanfattning

Den svenska titeln på denna avhandling är ”Vedförnans funktion och dynamik i boreala skogsbäckar”. Den handlar om (1) vedförnans effekt på bäckfårors morfologi och retention av organiskt material, och (2) vedförnans dynamik och dess relation till strandskogens historia och sammansättning. De studerade områdena är belägna i mogen, produktiv skog i den boreala delen av Sverige.

Mängden ved visade sig vara viktig för att förklara frekvensen av organiska dammar, uppdämd vattenyta, andelen uppdämda vattensamlingar formade av ved och variationen i bäckfårans bredd. Vattensamlingar som dämts upp av vedförna hade större area och residualdjup än vattensamlingar formade av andra objekt. Bäcksträckor som rann igenom naturskogar (med få spår av skogsbruk) hade grövre och längre vedbitar, mer vedförna, fler organiska dammar och fler vattensamlingar som dämts upp av vedförna än bäcksträckor som rann genom skogar som blädats.

Hur vedförnans kvalitet och kvantitet påverkats av tidigare skogsbruk analyserades med hjälp av dendrokronologiska metoder. Huggningar och frånvaro av bränder efter 1831 resulterade i lägre tillförsel av vedförna samtidigt som den med tiden alltmer kom att härröra från gran i stället för tall. Uppehållstiden för vedförna (bitar >10 cm i diameter i basändan) i bäcken var lång och de äldsta daterade bitarna av tallved och granved var över 300 respektive 100 år.

Vedförnans dynamik undersöktes genom jämförelser mellan bäckfåror och strandskogar i naturskogar respektive brukade skogar. Vedvolymerna i bäckfårorna överskred, men var korrelerade med vedvolymen i strandskogen. Måttlig införsel genom stranderosion och avsaknad av sluttningsprocesser på grund av grova substrat och flacka omgivningar visar att införsel av vedförna till bäcksträckor i stor utsträckning sker genom samma processer som verkar i strandskogen.

Retentionen av organiskt material i bäckfåror undersöktes genom utsläpps- och fångstförsök i många sträckor under olika flöden och med olika storlekar av lövattrapper. Sextiåtta procent av variationen i retention kunde förklaras med en regressionsmodell som inkluderade flöde och lövattrappernas storlek. Mellan 44 och 80% av variationen i retention mellan sträckor kunde förklaras med framförallt bäckfårans form, mängden grus på bottnen och några vedvariabler. En analysmodell visade på en ökning av medeltransportlängden med 22 till 53% i brukade skogar jämfört med naturskogsförhållanden och i ett scenarium med liten mängd ved ökade medeltransportlängden med 38 till 99% med högre ökning för högre flöden och större lövattrapper.

För att återfå mer naturliga förhållanden i bäckfåror behövs ett skogsbruk och sådana restaureringar som kan öka mängden vedförna som i sin tur återskapar strukturer och ökar retentionen av organiskt material.

Introduction

Woody debris in rivers and streams influence fluvial processes, channel morphology and biota. Human activities have altered the amounts of woody debris in many rivers and streams; hence it is vital to understand its function and dynamics, particularly in exploited areas where management and restoration actions are possible. The importance of woody debris in aquatic ecosystems has received much attention during the last decades since it was first highlighted in the Pacific Northwest. Functions and dynamics of woody debris in lotic ecosystems have since then been a research topic in many regions of the world (Montgomery and Piegay, 2003), although most of the basic knowledge still derives from studies in North America, particularly the Pacific Northwest (Bilby and Bisson, 1998). The information gained from these studies is fundamental for our understanding of natural fluvial processes and the roles of woody debris. Transferring this knowledge to other regions, for instance the boreal forests of Sweden, must be done with caution because of major differences in tree species, flow regimes, forest history and dynamics, and climate and geology.

In terrestrial ecosystems of boreal Fennoscandia, woody debris is important for many forest-dwelling species and its dynamics has therefore received much attention (Samuelsson et al., 1994). However, studies concerning functions and dynamics of woody debris in streams are still limited. Some of the knowledge achieved from terrestrial studies may nevertheless be useful for our understanding of woody debris in aquatic environments.

Definitions of woody debris and influence on fluvial processes

Woody material derives from plants with a high content of cellulose and lignin (Harmon et al., 1986). The definition of woody debris differs between studies depending on the objectives of the study and the size of the watercourse. An often used size definition is >10 cm in diameter and >1 m in length. This material is usually termed large woody debris (LWD). Wood in rivers and streams represents physical obstructions that are able to alter water flows. Hydraulically, it increases channel roughness and flow resistance (Curran and Wohl, 2002) that affects fluvial processes. Woody debris differs in many ways from boulders, bedrock outcrops, or sediment accumulation that also act as physical obstructions. The typically elongated woody material has different characteristics and dynamics and it derives exclusively from the terrestrial environment. The abundance is easily altered by humans by active removal, modifications of channels or by alterations of the source. The size, orientation, aggregation, and stability of wood pieces are of major importance for their function (Bilby and Bisson, 1998). Possibly the most studied influence of woody debris in rivers and streams is its ability to create and modify pools, and their abundance, geometry and function. Various definitions of pools exist but they are generally described as channel units with low water velocities, gentle gradients, and with a depth generally greater than in other channel units. Pools are created and modified mainly by two processes, namely damming of water and scouring of channel sediment (Bisson et al., 1982). Another important function of woody debris, closely related to its role in pool formation, is its ability to create a stepped longitudinal profile, resulting in a stairlike channel (Keller and Swanson, 1979). In these drops, energy is dissipated and less energy becomes available to transport sediment (Heede, 1972). Several studies have documented that huge amounts of sediments of organic and inorganic origin are stored in channel structures created by woody debris or directly associated with woody debris (Bilby, 1981; Piegay and Gurnell, 1997). Other influences include effects on riparian vegetation development (Fetherston et al., 1995), formation of gravel bars and islands (Abbe and Montgomery, 1996) and stabilization of river banks.

Many stream ecosystems are dependent on organic matter as an energy and nutrient source (Vannote et al., 1980). Efficient use of this material requires that it is retained in the channel. Storage of coarse particulate organic matter (CPOM), with non-woody particles >1mm in size, levels out the large annual variations in input. In many studies, woody debris has been proven to be of significant importance for the retention and storage of CPOM (Bilby and Likens, 1980; Ehrman and Lamberti, 1992; Raikow et al., 1995). Other ecological benefits are the creation of various habitats for aquatic species, affecting their competition, densities, and survival (Maser and Sedell, 1994). The importance of woody debris for the formation of fish habitat is most studied (Bisson et al., 1987).

Wood dynamics

Many factors influence the quantity and quality of woody debris in rivers and streams, resulting in a wide range of patterns and loadings in different systems (Harmon et al., 1986). Wood abundance is a function of the difference in the rates of supply and depletion. In a review of woody debris in rivers and streams, Naiman et al. (2002) specified these as two major knowledge gaps. The input of wood to streams depends on a number of factors, for instance the species composition of riparian forests, soil stability, valley form, climate, lateral channel movement, forest management history and input by transport from upstream reaches (Bisson et al., 1987). Several North American studies have shown that timber harvest decreases the amount of woody debris in rivers and streams, but may initially add substantial quantities of smaller-sized logging residue (Bilby and Bisson, 1998). The high content of lignin and cellulose, and high volume-to-area ratio result in a slow decomposition of woody debris compared to other organic materials. In contrast to the terrestrial environment, only few studies have evaluated residence times and decay rates of woody debris in rivers and streams. Fully submerged pieces decay slower than others due to low oxygen levels (Triska and Cromac, 1980) and wood, when fully waterlogged or otherwise in environments free from oxygen, can be preserved for thousands of years (*cf.* Grudd et al., 2002). Decomposition of dry wood is also slow because the decomposers require moisture. Much of the wood stored in rivers and streams is only partly waterlogged and shifts in the water level create variable opportunities for decomposition in channels. Additionally, the physical abrasion of wood caused by water erosion and transport may be important. Transport generally decreases with decreasing channel sizes and increasing sizes of woody debris (Swansson et al., 1984). Species with different nutrient contents, densities and sizes have different decay rates. Generally, deciduous species decay faster than conifers (Hyatt and Naiman, 2001).

The Boreal Fennoscandia and Its Human Influence

Geology

The Baltic shield underlies much of the boreal Fennoscandia outside the mountainous Caledonides. It contains nearly 2000 million years old Precambrian bedrock of which large areas consist of metamorphosed sediments (mostly greywacke) and volcanic rocks (mostly acidic). The relief of the landscape results from various combinations of old tectonic lines, remnants of peneplains, deep weathering, and glacial erosion. The soil layers are typically thin and mostly originate from the latest glaciation and its recession some 10,000 years ago. The boreal landscape of Sweden has since experienced an isostatic rebound with the former highest coastline at present altitudes between c. 200-285 m. The distribution of soil types is strongly influenced by topography. In boreal Sweden, fluvial and glaciofluvial deposits, outwash, and fine grained sediments are mostly found below the highest coastline within the larger river valleys and near the coast. Glacial till, mostly sandy, covers 75% of the Swedish land surface and most of this area is forested. Lakes cover 9% and peat covers 15% of the land area (Fredén, 1994).

Forests

The boreal forest biome is circumpolar on the northern hemisphere between the polar and temperate regions. The boreal forest ecosystems are adapted to large variations in temperature, and the forest is dominated by coniferous species. Most of the Fennoscandian peninsula is included within this region where forests are dominated by Norway spruce (*Picea abies*) and Scots pine (*Pinus sylvestris*) (Esseen et al., 1997). Naturally, the geological and climatological settings together with various disturbances shape the large-scale pattern of regeneration and succession of the forest. Scots pine is typically found on drier sites and Norway spruce is more commonly found in richer mesic and moist sites. Most deciduous species in the boreal forest of Sweden, of which birch (*Betula* spp.) is the most abundant, are pioneer species. Pine is an important pioneer on drier sites whereas spruce is a late successional species that often dominates in fire refugia and forests in late succession stages. Forest fires are considered to be the major disturbance element within this biome (Zackrisson, 1977), but wind, herbivory, flooding, mass wasting, and climate variability are other agents.

Human influence on the forest landscape

The human population density in boreal Sweden has always been low in a European perspective and most people lived, and still live, along the coast and within the large river valleys (Helmfrid, 1996). Human influences on the landscape have nevertheless a long history and today the whole forest landscape is intensively managed, although forest continuity has prevailed at the landscape scale since the early Holocene. Human influences on the forest landscape before the commercial industrial exploration are not easy to estimate but are generally considered as low-intensive but spatially extensive. They include altered fire regimes, and altered herbivore populations by hunting and livestock breeding. An industrial exploitation of the boreal forests of Sweden that altered the forest structure by logging started approximately 200 years ago. The "timber frontier" moved across the landscape during the 1800s and large pine trees of good quality were selectively cut and in the 1900s smaller trees of both pine and spruce were utilized (Östlund, 1993). Deciduous trees have shorter fibers and were less useful in the paper and pulp industry. To maximize wood production, clear cutting forestry was introduced on a large scale in the 1950s (Ebeling, 1959) with management units of mainly coniferous species of similar sizes and ages. The rotation period in the boreal forest of Sweden is approximately 80 to 120 years and consequently, many of the forests that are harvested today are remnants of stands that were selectively cut prior to 1950.

Protected areas and today's management

Today, only minor areas of the productive forest land in the non-mountainous region are unmanaged. They are typically located in remote areas far from settlements and transport systems or within larger low-productive wetlands (Bernes, 1994). During the 1990s a more biodiversity focused forestry has been introduced as a result of the growing environmental awareness and the Swedish Forest Act from 1994 that states that production and environmental goals are equally important. This management policy includes goals of biodiversity maintenance, conservation of threatened species, and upholding of essential ecosystem functions and processes.

Human influence on the physical structure of drainage networks

In Sweden in 1764 it was declared that rivers, streams, and lakes should be "cared for" to avoid harmful damming by "floating peat islands, wreck forest, and fallen earth banks". For this reason it was declared that "all persons in the country should be forced…, on private and crown owned land, to clean and keep in their original channels, all larger and smaller rivers and streams". Little was probably done at that time to comply with this regulation, especially in remote areas, but the declaration illustrates the early view that obstructions should be removed from river and stream channels.

The commercial exploitation of the Swedish boreal forest resources required a system to transport the bulky and heavy logs. Initially, only timber close to the manufacturing and shipping sites near the coast could be utilized. Many rivers and streams contained sections that hindered effective transportation. Consequently, large forest areas could not be harvested. This was early realized and in the 1700s increasing efforts were made to "open up" the forests for exploration. Timber floating has a long history, but in the 1700s the first larger organized undertakings were performed in boreal Sweden (Norberg, 1977). From the 1800s many streams and rivers were continuously improved for timber transport by clearing of rocks and woody debris and later on also by the construction of means to improve transport, for instance deflectors and splash dams. Channel straightening and blocking of side channels were other improvements. The use of explosives, and later on heavy machinery, enhanced the alteration. The most intensive period of timber-floating was in the 1930s and the maximum length of the common float-ways was approximately 33,000 km

(Furuskog, 1943; Nilsson et al., in press), excluding reaches that were used more temporarily. After this period, mechanized transport on trucks and railroads gradually took over and most timber floating ended in the 1960s.

Drainage of forest and wetlands by trenching began in the mid 1800s, mainly as a method to improve forest growth. In the beginning of the 1900s, new forestry ideas, together with the belief that all drained wetlands were suitable for forest production, and government subsidies, inspired large scale drainage projects of mainly wetlands. During the 1900s, the yearly average length of produced ditches averaged approximately 4,000 km (Hånell, 1989) but the trenching method, depth and impact on the environment varied. Not only drainage of wetland occurred, clearings and excavations of small streams to improve their capacity to transport water were also common practices. Today, c. 15% of the wetland area of Sweden is drained (Bernes, 1993).

Headwater streams, i.e., streams with channel widths less than a few meters, encompass approximately 80% of the length of drainage networks. The natural drainage density in Sweden is roughly 1 km/km^2, equaling c. 400,000 km of channels. According to the length of the float-ways and temporarily used reaches, approximately 10% of the channel network, mainly the largest watercourses, have been modified to facilitate timber floating. A substantial proportion of the smaller channels has been cleared or excavated to increase their water transport capacity (c. 25% based on field observations). Adding the length of ditches created during the 1900s, another 400,000 km of open channels have been created. There are roughly 200,000 km of forest roads in Sweden (Helmfrid, 1996) that typically have ditches on both sides, adding yet another 400,000 km to the drainage network. In addition, many streams and rivers are regulated by dams and impacted by various constructions, bridges and road culverts. The surrounding, most natural channels have experienced various management operations in their riparian forests that have potentially altered their content of woody debris. This may have resulted in an extensive but unqualified modification of the channel network.

Natural variability as a template for management

The idea that the pristine conditions of a system could be used as a template for maintaining and restoring ecosystems and their functions is common in many environmental sectors (Swanson et al., 1994). If natural processes and their variability are maintained, ecosystems are likely to continue functioning. It is therefore necessary to study “natural” or “pristine” conditions to achieve information about temporal and spatial patterns and processes within various regions (Spies and Turner, 1999). This information can be used to develop management and restoration of impacted systems, such as stream channels. Since pure pristine conditions, defined as conditions without any human influence, do not occur, the least affected sites and historical sources of pre-industrial conditions could serve as substitutes.

Objectives

This thesis deals with different aspects of function and dynamics of woody debris in streams. The focus is on small streams that intersect old-growth and managed forested areas of boreal Sweden.

The specific questions are:

- How does woody debris in Swedish boreal streams affect channel morphology (**I**)?

- What are the similarities and dissimilarities in the dynamics of woody debris between stream channels and their adjacent riparian forests (**IV**) and how do the amounts and characteristics of woody debris compare between old-growth and managed forest sites (**I**, **IV**)?

- How has the riparian forest history influenced the amounts and characteristics of woody debris in stream reaches intersecting managed forests (**II**)?

- Are riparian trees zoned across the riparian zone of near-natural headwater streams, and how far away from the stream are its sources of woody debris (**IV**)?

- Which reach-scale characteristics of stream channels are important for the retention of coarse particulate organic matter and to what extent can retention be predicted (**III**)?

- What is the loss of retentiveness in boreal headwater streams due to reduced amounts of woody debris (**III**)?

Methods

Study areas

The study sites in this thesis are situated in the middle and northern boreal zone in Sweden (Ahti et al., 1968). The streams and their surroundings were selected in mature productive forests and they are all situated above the postglacial highest coastline. In paper **I**, **III**, and **IV**, data from old-growth and managed forest streams were compared. Sites with direct man-made disturbances others than forestry were avoided. Streams intersecting old-growth forests had no or minor influence of direct riparian forest management by logging, whereas the streams intersecting managed forest had faced abundant selective loggings in their riparian forests. The study in paper **II** and the experiments in paper **III** were both undertaken in managed forest streams. All the studied stream reaches have moderate to high channel gradients, low sinuosity, and generally a high proportion of coarse bed material. All streams, except for a few reaches in study **III**, intersect morainic deposits. They all have poorly incised valleys and lack developed floodplains. These characteristics are typical for many streams in productive forests over large areas of boreal Fennoscandia.

In the studied region, mean annual temperature is approximately 0–3°C and the annual precipitation is 600–700 mm of which 30–40% arrives as snow. The snow covered period is 150–200 days/year (data from 1961–1990; Raab and Vedin, 1995) and the streams are ice-covered several months of the year. During late winter and late summer discharge usually reaches base flow levels. Snowmelt in spring results in a flood, and flooding may also occur after heavy rains in summer and autumn (Raab and Vedin, 1995).

Field measurements and data analyses

Length, basal, and top diameters of woody debris in streams were inventoried during base-flow conditions. Depending on the objectives of the papers, different minimum sizes were used. To evaluate functions and dynamics of woody debris, additional data about the wood pieces were also included. Those were species (**I, II, IV**), orientation (**I**), influence on water flow (**I**), decay class (**I, II, IV**), fracture ends (**I, II**), bole shape (**II, IV**), and if the piece was included in a debris dam (**I–III**). Remnants of bark and other external characteristics were used for identification of tree species. In paper **II** wood anatomy was checked in microscope to verify field identification. Dendrochronological methods were used in paper **II** to date the year of mortality of the in-channel pieces of woody debris, as well as forest fires and forestry activities that had taken place in the surrounding riparian forest.

All papers included measurements of stream characteristics such as bankfull channel width, channel gradient, and sinuosity. Channel morphology was related to the amounts of woody debris (**I**) and CPOM retention (**III**). Channel units were identified and their lengths and widths were measured. Pool studies also included mean depth, maximum depth, and depth at downstream hydraulic control (Lisle, 1987). The channel substrate was quantified by visual estimates of boulder cover (**I**) and by point measurements of stream channel substrates divided in size classes (**III)**. The retentiveness of the stream reaches in paper **III** was estimated using release and capture experiments of leaf mimics of different sizes and during different discharges. In paper **II** and **IV** dynamics of woody debris in riparian forests and stream channels were compared and the riparian forest was analyzed using strip transects.

Major Results and Discussion

Functions of woody debris

Woody debris had substantial morphological effects in the studied stream channels, despite their high contents of other physical obstructions (boulders), low erosiveness, and amounts of woody debris that generally were lower than in most North American studies (*cf*. Harmon et al., 1986). Wood variables were found to be important predictors of the frequency of debris dams, pool area, the proportion of pools formed by wood, and variation in bankfull channel width (**I**). Approximately 1/3 of the pieces of woody debris was included in debris dams and this proportion increased in streams with higher channel gradients and channel widths, i.e., in channels with higher abilities to transport wood pieces. Wood-formed pools had larger surface areas and residual depths than pools formed by other agents, suggesting that these pools are more important for stream biota (Hawkins et al., 1993; Bisson et al., 1987). The percent cover of pools increased as wood loadings increased but decreased as the gradient increased. Similar responses of increased wood amounts have been found in other studies (Beechie and Sibley, 1997).

A majority of the pools were formed by damming, mainly upstream of debris dams (**I**). This finding contrasts with most other studies where scouring is the prevalent pool-forming mechanism (Montgomery et al., 1995). This may be explained by the high content of coarse channel substrates in boreal Swedish streams that inhibit scouring. Coarse substrates that result in low input by bank cutting (*cf*. Murphy and Koski, 1989), together with small tree sizes compared to most North American studies, may explain the lower volumes of woody debris in the channels. In many areas headwater streams are often non-perennial, constrained within steep valleys, and are strongly influenced by various slope processes. This description does not apply to boreal Swedish conditions. Most small streams are perennial, few are constrained and thus slope processes are rare.

Streams in old-growth forests had higher amounts of wood, and more debris dams and wood-formed pools. In the old-growth forest streams the average frequency of debris dams was 7.6/100m, and 39% of the pools were formed by woody debris. The corresponding figures for the managed forest streams were 4.2/100m and 16%. The average bankfull volumes of wood recorded in the streams intersecting old-growth forests were 93.7 m^3/ha, and the frequency of woody debris was 66/100 m. The same figures for the managed forest streams were 24.8 m^3/ha and 36/100 m. The stream reaches intersecting old-growth forest had generally coarser and longer pieces of woody debris compared to the managed forest streams (**I**).

Comparisons of woody debris between stream channels and riparian forests

The results of paper **II** indicated that the history of fires and management in the riparian forest resulted in lower input rates and a gradual shift in the tree species composition over time. The oldest piece of woody debris (>10 cm in basal diameter) of pine had outer rings from the late 1600s and the oldest piece of spruce derived from late 1800s. This suggests long residence times for coniferous woody debris in stream channels, but the mean residence times cannot be estimated in this system because of the variable input over time.

Wood volumes recorded in the stream channel exceeded, but were related to the volumes found in the riparian forests (**II, IV**). This applied to sites in both old-growth and managed forests, but the pattern was more evident in the old-growth sites (**IV**). Limited input of woody debris by bank cutting, and absence of slope processes because of course substrates and flat stream surroundings together with the above findings suggest that the mechanisms responsible for input of woody debris to stream channels are similar as the mechanisms responsible for input to the riparian forest floor. This suggestion is supported by the fact that in-channel volumes of woody debris, separated to tree species, were better correlated with terrestrial volumes of woody debris than with volumes of living trees (**IV**). The higher volumes in the stream channels compared to the riparian forest floor may thus be a result of slower decay of woody debris in the channels. Consequently, much of the information gained from studies on woody debris dynamics in upland forests can probably also be used for predictions of input of woody debris to stream channels.

Forest history and woody debris in a stream intersecting a managed forest

The results in paper **II** indicate variable input of woody debris over time, and a pattern that can be explained by cutting operations and an altered fire regime in the riparian forest. In the studied stream reach pine seems to have been more abundant previously, probably because the frequent forest fires in the riparian forest favored pine trees. Later on, around 1800, the first cuttings of pine trees were performed. The timing and objectives of the cuttings are consistent with the general forest history of the area and historical documents (Östlund, 1993; Östlund and Linderson, 1995). The input of woody debris from pine declined in this period, and regeneration was probably inhabited by the lack of fires after 1831. From the late 1800s, input of pine was scarce, most contributions stemmed from spruce and coincided with cutting operations in the riparian forest. After the more recent and possibly more extensive forest operations in the mid 1900s the input of woody debris from conifers was limited. A small number of dated birch pieces all gave young dates. Most of the pine wood found in the channel today is old and derives from the time before large-scale cuttings; in addition, those trees regenerated during a period when fires were still present. The dated spruce wood originated from a time when repeated selective cuttings were performed in the riparian forest. Although traces of beavers appeared along many of the studied streams, only a low percentage of the wood material was added by beavers (**I, II**). More extensive influence of beaver is typically found along reaches where beaver have dams and huts, i.e., slow-flowing reaches intersecting peat or fine sediments.

Lateral zonation of trees along headwater streams

In the old-growth riparian forests studied in paper **IV**, a diffuse zonation of trees across the riparian zone was found with slightly higher abundances of deciduous and lower abundances of pine trees close to stream channels. Thirty percent of the variability of the basal area of pine trees and 9.3% of the variability of stem density of deciduous species could be explained by the distance to channel edge. Coniferous tree species, mainly spruce, dominated in the riparian forests and no major differences were found in the forest composition adjacent to the streams than would be expected from upland forests.

Source distances of instream woody debris

Measurements of distances and estimates of heights of riparian trees in paper **IV** indicate that most of the trees that potentially can reach the channel as woody debris derive from a narrow zone along the streams. If assuming random tree fall (*cf*. Van Sickle and Gregory, 1990), most trees (c. 80%) will derive from the 10-m wide zone closest to the channel edge, and nearly all wood (99.5%) that can enter is found within the 15-m wide zone closest to the channel. Possibly, trees that are growing on the channel edge have a higher probability to fall towards the channel (see discussion in **II** and **IV**). If that is the case, an even larger proportion of the wood derives from close sources.

Retention in boreal headwater streams

Predictions of the short-time retention of CPOM in stream channels can be made with quite a high accuracy according to the analyses in paper **III**. Sixty-eight percent of the variation in retention could be predicted by a multiple regression model including discharge and leaf mimic size. In the model discharge was the most important variable.

Divided in all possible combinations of discharge and leaf mimic size, the variation in retentiveness among reaches could to a large extent (44–80%) be predicted by variables describing stream channel configuration, substrate, and woody debris. In general, channel constraint (bankfull depth/bankfull width), gravel cover, and woody debris variables were the most important. Retention increased as channel constraint decreased and gravel coverage and woody debris variables increased. Channel constraint was more important for the models explaining smaller particles, and woody debris variables were generally more important for predicting retention of larger-sized particles. Among the woody debris variables, the bulk volumes of debris dams were important for predicting the retention during high flows, and single pieces were more important during lower flows. For smaller particles at lower flows the residual depth of pools was included in the models. Hyporheic filtration may be the process that makes gravel-sized substrates important.

To our knowledge, paper **III** presents the first predictive models for CPOM retention. Their direct applicability may be limited to a narrow range of stream characteristics but they provide a tool that can be used to estimate possible outcomes of changes in wood amount, CPOM size, and discharge. According to the models, larger-sized particles are relatively more sensitive than smaller ones to changes in wood amount, and smaller particles are more sensitive to changes in discharge. The use of only leaf-sized material in studies of retention in streams does not give the full picture and may overestimate the importance of woody debris.

Loss of retentiveness following reduced amounts of woody debris

A Partial Least Squares (PLS) model (Geladi and Kowalski, 1986) was used in paper **III** to estimate the potential loss of retentiveness in streams surrounded by managed forests compared to old-growth conditions due to lower amounts of in-channel woody debris. The model that included the wood variables frequency, loading, volume, and debris dam frequency was statistically significant but could only explain 23% of the variability in retentiveness. This is because many other factors influence retention. Although the predictive ability was low for individual reaches, conclusions about general patterns can be made. The PLS model predicted different decreases in retention depending on particle size and discharge with generally larger increases for higher discharges and larger particle sizes. This corresponds to the results of the multiple regression models. The estimate from the PLS model suggests an increase in mean CPOM transport distances by 22 to 53% in managed forest streams compared to old-growth conditions. In a realistic low-wood scenario, mean transport distances increased by 38 to 99% (**III**).

*Upstream view of the retention experiment stream in paper **III**. The stream is situated in a spruce-dominated managed forest in central Sweden. The average bankfull width of this reach is 1.6 m.*

Concluding Remarks, Forestry Implications and Further Research

The main conclusions of this thesis are that woody debris is an important component in Swedish boreal forest streams that influences channel morphology and retention of organic material. Selective loggings in riparian forests have caused a reduction in the amount of woody debris in stream channels, and the woody debris has changed towards smaller sizes and altered species compositions. In most streams this has resulted in fewer debris dams, a lowered proportion of wood-formed pools, and decreased retention capacities of organic material, especially during high discharge and of larger-sized fractions. Riparian old-growth forests show a weak lateral zonation of trees and have many similarities with upland forests. Processes of recruitment of woody debris to streams are similar as those in upland forests. Conifer woody debris has long residence times in stream channels and decay is slow compared to the riparian forests.

On a landscape level, only small wood amounts would be needed to restore levels of in-channel woody debris due to the low areal extent of the streams. To restore headwater streams with an average bankfull width of 2 m to old-growth wood volumes (from 25 to 94 m^3/ha, data from paper **I**) would require c. 14 m^3/km^2 if assuming a drainage density of 1 km/km^2. For comparison, increasing woody debris volumes in a forest area of 1 km^2 by 10m^3/ha would require 1000 m^3. Management that increases the wood recruitment potential of the riparian forest, and active addition of wood, could be used to increase woody debris amounts, recreate stream channel structures and increase the retention capacity of organic material. Site productivity of the riparian forest can potentially be used to estimate woody debris volumes in stream channels under pristine conditions. Management should target the immediate surroundings of the stream when creating the basis for future supply of woody debris. Increased proportions of pine trees will provide long-lived woody debris that dampens the effect of temporal variations in wood supply.

Although the impact of lowered amounts of woody debris in stream channels on the aquatic ecosystems may be severe, exploration of the function and dynamics of woody debris in boreal forest streams of Fennoscandia has been limited. This thesis contains some of the first results from this region and provides a basis for further research. More extensive research targeting the main questions in this thesis should include larger sample sizes with a range of stream sizes that intersect different substrates and forests of different types, ages and histories. For instance, what are the effects of woody debris in larger systems? How would a natural fire regime influence the development of forest adjacent to streams and the input of woody debris to stream channels? What is the influence of woody debris on the long-term flow of energy and material in drainage networks, on stream water chemistry, and on ecosystems? Alea jacta est.

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