# Chapter 14
# Water Quality

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## Abstract

- Conventional forest operations can exert significant impacts on the hydrology and water quality of downstream aquatic environments.
- Few research results have been published on the impacts of continuous cover forestry (CCF) on water quality.
- CCF could be useful for reducing nutrient, carbon, and suspended solid exports in waterways.
- CCF may be a better alternative to rotation forestry (RF) on mineral soils and drained peatlands.
- Further research is needed on the many processes controlling nutrient and carbon exports in CCF and RF.

**Keywords** Upland soil · Peatland · Water loading · Brownification · Forest hydrology

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## 14.1 How Does Forest Management Impact Water Quality?

Conventional forest operations in Fennoscandia typically follow a forest rotation management approach, involving clearcut harvesting, subsequent soil preparation treatments, planting, and one or more thinnings. These practices can exert significant impacts on the hydrology and water quality of downstream aquatic environments. Loadings, i.e., the waterborne exports of elements to water courses, can arise from the release of suspended solids and nutrients resulting from these forestry operations. In conventional rotation forestry (RF), the most substantial loads tend to occur following regeneration cuttings, particularly clearcuttings with soil preparation (Nieminen 2004; Kaila et al. 2015; Nieminen et al. 2015), ditch network maintenance, DNM (Nieminen et al. 2010, 2018a), and forest fertilisation activities (e.g., Piirainen et al. 2013). On mineral soil sites, the increase in nutrient exports caused by harvesting and soil preparation is due to the increase in erosion, the release of nutrients due to decomposition of harvesting residues, and the lack of nutrient uptake by trees and other vegetation (Kreutzweiser et al. 2008). The exports are commonly greatest in the first years after the treatment and decrease over time. In drained peatlands, the exports caused by felling are largely due to the rise in the water level, because the harvest results in reduced evapotranspiration. This will in turn change the release of elements because of altered chemical reactions under anaerobic conditions (redox reactions) in the peat (Nieminen et al. 2017a). Erosion can also be significant, especially in areas treated by ditch mounding.

## 14.2 Peatland Forestry and Water Quality

Forestry on drained peatlands has a great economic significance, particularly in Finland, where about 25% of the productive forest land is on this type of soil. In Sweden and Norway, the corresponding figures are 14% and 3%, respectively. Forestry on drained peatlands also causes significant impacts on water quality. Historically, the initial drainage of peatlands was regarded as one of the most significant forestry practices influencing the quality of surface waters. It was previously believed that post-drainage export levels would return to those of an undisturbed peatland within 10–20 years (Finér et al. 2010), but current understanding suggests that these exports will remain consistently higher than the background levels of pristine peatlands (Nieminen et al. 2017a; Finér et al. 2021).

This additional export resulting from drainage has been estimated to exceed by a considerable margin the combined exports resulting from DNM, fertilisation, and timber harvesting (Nieminen et al. 2017b; Finér et al. 2021). The mechanisms behind the additional export caused by drainage are poorly understood, but the decomposition rate of peat is known to strongly depend on the water table level, which determines the oxygenation state in the peat (Ojanen and Minkkinen 2019). As the trees within the stand grow after drainage, their evapotranspiration (ET) increases (Sarkkola et al. 2010), the water table level falls, and more oxygen flows into the deeper peat layers, increasing decomposition. The nutrients released from deep peat layers are primarily not usable by trees and other vegetation, so are more likely to leach into groundwater. Several recent studies show that the nutrient exports from drained peatlands can increase over time (Nieminen et al. 2017b, 2023; Räike et al. 2019).

Drainage significantly increases nutrient exports over time, by altering the hydrological dynamics within a catchment. In their pristine state, minerotrophic, nutrient-rich peatlands have the capacity to retain mineral nutrients carried by the water flowing from the catchment area above them. However, after drainage, these nutrients released from the catchment area can swiftly bypass the vegetation and peat of the minerotrophic peatlands and are directly transported into ditches and subsequently into water courses, without any interaction with or filtration by the peatland ecosystem (Sallantaus 1988).

The importance of afforestation and the increase of forest biomass as a possible source of organic carbon export and the brownification of water bodies has been highlighted (Finstad et al. 2016; Škerlep 2021; Nieminen et al. 2021). In recent decades, the forest stands have matured, and many forests have become spruce dominated. This ‘sprucification’ has increased the amount of recalcitrant organic needle and root litter fall in the forests, which in turn may contribute to the leaching of organic carbon and increased brownification (Kritzberg et al. 2020).

## 14.3 Effects of Standard Forestry Treatments—Peatlands in Focus

DNM has been estimated to produce more than 90% of the export of suspended solids caused by forestry treatments (Finér et al. 2010; Marttila and Kløve 2010). Particulate organic and inorganic phosphorus is also leached along with the solid matter, and is estimated to average about 0.1% of the leached suspended solids (Finér et al. 2010). The peak export of suspended solids is 1–2 years after the treatment (Nieminen et al. 2010).

Suspended sediments (mineral particles, organic matter) are widely recognised for their detrimental impact on downstream aquatic ecosystems, by increasing turbidity and brownification of water and filling up watercourses. They can harm aquatic habitats, suffocate spawning beds, lead to fish population declines, and significantly alter the abundance and diversity of aquatic invertebrates (Annala et al. 2014; Kjelland et al. 2015; Rajakallio et al. 2021). Their detrimental impacts can endure over many years; often it may take several decades before habitats can recover, assuming recovery occurs at all. Sediment erosion, transport, and deposition are identified as one of the most serious, yet most understudied, aspects of water quality in Sweden (Futter et al. 2016).

Even though DNM increases the export of inorganic nitrogen (nitrate, ammonium) to some extent, the total dissolved nitrogen leaching does not usually increase, because the leaching of dissolved organic nitrogen (DON) usually decreases (Laudon et al. 2023). Also, the export of dissolved organic carbon (DOC), which affects the water colour, will not increase, and may even decrease (Joensuu et al. 2002; Nieminen et al. 2018a). However, over the long term, the leaching of organic carbon is greater from drained peatlands than from pristine mires (Nieminen et al. 2021).

Clearcuttings on peatlands increase the leaching of all main nutrients; for example, nitrogen export is about five times greater from peatlands than from mineral soil sites (Nieminen 2004; Finér et al. 2010). In peatlands, the harvest of evapotranspiring tree stands quickly raises the water level, which significantly increases the risk of leaching of nutrients and organic carbon. When the water level rises, i.e., when the previously aerobic peat layer becomes anaerobic, redox reactions start in the peat soil, which can especially increase the leaching of phosphorus, iron, organic carbon, organic nitrogen, and ammonium nitrogen (Kaila et al. 2014; Koskinen et al. 2017). There are observations of large exports especially from nutrient-rich peatland forests after regeneration harvestings and restoration treatments, which both raise the water level (Nieminen et al. 2015, 2020).

The leaching caused by the rise of the water level is difficult to mitigate by water protection methods currently used in practical forestry, such as sediment pits and ponds, especially because they do not retain the carbon and nutrients transported in dissolved organic form (Haahti et al. 2018). The rise of the water level can be prevented through more efficient drainage, but this in turn would increase the export of suspended solids, particulate nutrients, and heavy metals (Joensuu et al. 2002; Nieminen et al. 2010). Effective drainage would also increase the decomposition of peat, thereby increasing carbon and nutrient exports to recipient water bodies (Nieminen et al. 2023) and atmospheric carbon emissions (Ojanen and Minkkinen 2019).

An alternative to drainage for controlling water level is to retain evapotranspiring trees in the forest stand. Remaining trees and even understorey vegetation may also capture the nutrients released from harvest residues and soil after harvesting. This could be attained through continuous cover forestry (CCF), in which large-scale clearcuttings are avoided, and selection cutting, strip cutting, shelterwood cutting and small gap cuttings are instead used to retain evapotranspiring vegetation.

## 14.4 Can CCF Decrease Water Loading?

In peatlands, the CCF concept operates on the principle that tree removal should not significantly impact the evapotranspiration (ET) capacity of the stand. In this way, the effects on water table levels are moderate, and the drainage would remain sufficient to avoid affecting tree growth (Nieminen et al. 2018b). The remaining trees within the stand also play a crucial role in reducing nutrient leaching, as they capture some of the nutrients released, particularly from the decomposition of harvest residues.

CCF is suggested to reduce leaching from peatlands because it would reduce the need for DNM, and because the water level in the peat would be somewhat higher on average than in stands managed with conventional RF. This would reduce the decomposition of peat and thereby the release of nutrients, especially from deep peat layers. CCF also has potential to limit another form of soil disturbance, namely site preparation. This, however, hinges on the success of natural regeneration in CCF forests, which departs from the conventional artificial regeneration approach commonly practiced in Nordic forestry. Traditional site preparation, often involving techniques like disc-trenching, has been associated with adverse impacts on water quality, such as increased DOC export (Schelker et al. 2012) and elevated levels of methylmercury (Eklöf et al. 2014). By reducing the need for site preparation, CCF not only benefits water quality but also promotes recreational value and biodiversity by minimising physical disruption to the site (Fig. 14.1).

There are no research results on the loading effects of CCF practised on mineral soils, and only a few results relating to peat soils. Load estimates based on thinning cuttings of RF cannot be presented, because they have not been empirically studied. However, bearing in mind that the exports caused by clearcutting on mineral soil sites have been estimated to be relatively minor (Kreutzweiser et al. 2008), the water quality effects of CCF can also be expected to be minor.

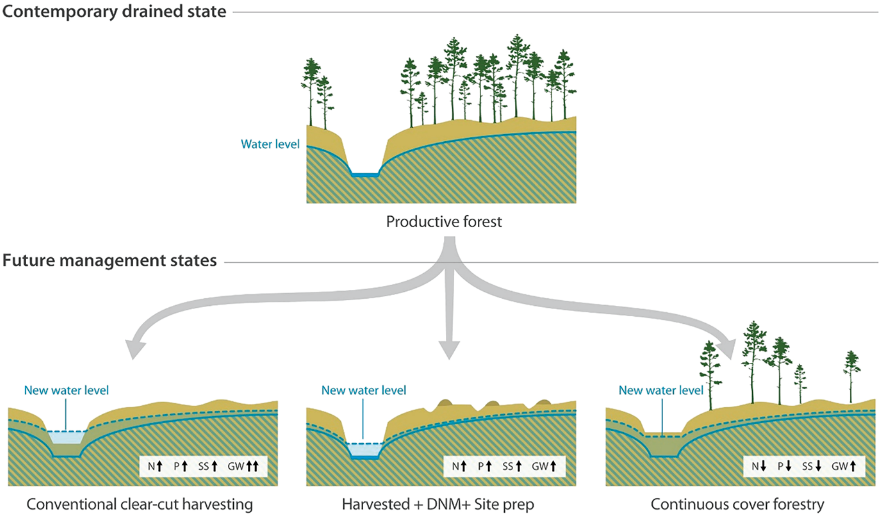

**Fig. 14.1** Conceptual model of the effect of forest management methods on the ground water table level (GW) and the exports of nitrogen (N), phosphorus (P) and suspended sediments (SS) in drained peatlands. DNM = ditch network maintenance; Site Prep = site preparation (original figure: Kritzberg et al. 2020, CCBY 4.0, link to the license: creativecommons.org/licenses/by/4.0/)

In Alberta, Canada, partial cuts showed intermediate decreases in ammonium ($NH_4^+$) in the forest-floor soil between uncut and clearcut sites of both deciduous and coniferous stands, as well as for phosphate ($PO_4^{3-}$) in forest floor soil in the coniferous stands (Lindo and Visser 2003). In both deciduous and coniferous stands, nitrate ($NO_3^-$) in the forest floor soil was elevated in partial-cut corridors and clearcuts compared with partial-cut patch and uncut treatments (Lindo and Visser 2003). In Québec, partial harvesting (corresponding to one-third and two-thirds removal of tree basal area) in aspen stands resulted in lower potential mineralisation of nitrogen and a lower relative nitrification index (net $[(NO_3^-)\colon (NO_3^- + NH_4^+)]$ production ratio) in the forest floor soil, compared to clearcutting (Lapointe et al. 2005).

Finnish and Canadian studies examined the impact of different partial harvest treatments on water table level in boreal settings. Roy Proulx et al. (2021) found that a 40% basal area partial harvest in a Canadian black spruce stand did not affect water table level 1 year later. Leppä et al. (2020) showed that removing up to 70% of basal area in Finnish Norway spruce sites had minimal impact on water table level, thanks to rapid field layer vegetation growth offsetting ET loss by tree harvest (Leppä et al. 2020). Pothier et al. (2003) found that cutting 50–60% of basal area in red spruce-balsam fir sites promoted vegetation regeneration and water table recovery compared to clearcutting. Päivänen and Sarkkola (2000) found no significant water table impact from 30% stand removal, rendering DNM to maintain drainage conditions after harvesting unnecessary. Older studies had similar findings on partially harvested sites (e.g., Heikurainen 1966; Päivänen 1982).

Recent Finnish research suggested strip cuts could maintain lower water table levels than clearcuts, depending on soil conductivity and stand density (Stenberg et al. 2022). While not as effective as selection harvesting in maintaining sufficiently low water table levels for undisturbed tree growth without DNM, strip cuts could be used as a special type of CCF for shade-intolerant tree species that cannot be managed by selection harvestings (Saarinen et al. 2020). CCF appears effective in controlling water table levels in many contexts but requires further testing across various geographical and soil settings, along with improved modelling, before being adopted for drained forested peatlands on a larger scale.

In the above experiments, phosphorus exports after strip-cutting on nutrient-poor pine peatland sites were lower than the exports shown in earlier clearcutting experiments, but not clearly lower compared to all clearcutting experiments. Nieminen et al. (2023) suggest the amount of harvested volume per catchment area could be a factor that correlates with the variation in nutrient exports more strongly than the specific harvesting method, regardless of whether it involves clearcutting, strip-cutting, or single-tree harvesting. The amount of harvested volume is directly related to the amount of harvest residues, the rate of decrease in nutrient uptake, as well as the rate of soil-water level rise following harvesting.

Based on process-based modelling and nutrient-export coefficients for different forest operations, Nieminen et al. (2023) investigated the regional effects of CCF and RF on nitrogen and phosphorus exports from forested catchment areas in Finland. They employed the MONSU forest planning model (Pukkala 2011) to simulate forest development and management operations on approximately 15 million hectares of forests over a 50-year projection into the future. According to the results, the transition from RF to CCF would clearly reduce water loading, both when following the practical forest management guidelines of Finnish forestry and when harvesting volumes are kept at the current level. The exports from forestry on drained peatlands were significantly greater than from upland sites, but the transition to CCF would nevertheless decrease the export per hectare by approximately the same amount on uplands and peatlands over the next five decades. The largest load benefits from CCF would be reached in southern Finland, where the climatic conditions are more favourable and where harvesting volumes from clearcuttings are larger and water table levels in peatlands are lower than in northern Finland (Nieminen et al. 2023). Nevertheless, the study underscores the necessity for further examination of the impacts of forest management on water quality. Experimental studies would be needed on various harvesting and tillage methods, as well as greater understanding about the processes influencing the release of exports, particularly from drained peatland forests.

## 14.5 Risks Associated with CCF

So far, we have highlighted potential benefits of CCF on peatlands, but it is also important to consider associated risks and address unanswered questions before advocating for widespread CCF implementation in Fennoscandia. One major concern is the risk of damage caused by heavy off-road forestry machinery, with shorter intervals between use for harvesting compared with RF. Peatlands are highly vulnerable to rutting, leading to water channelisation, creating hotspots for methylation of mercury , and erosion (Eklöf et al. 2014). Their low bearing capacity makes them more sensitive than other boreal soils (Ågren et al. 2014). Traditionally, rutting is avoided by harvesting in frozen winter conditions, but with warming winters this strategy may become less effective. CCF may not allow the use of branches and stems from less profitable trees to create haul roads and protect against rutting, as these trees are typically saved for later selection harvestings (Andersson et al. 2016).

Tree species composition may be difficult to maintain with some CCF methods. Norway spruce, a shade-tolerant secondary tree species, contrasts with species like Scots pine and downy birch, which thrive in direct sunlight, typically regenerating after fire, storm felling, or clearcutting. Norway spruce could therefore become the dominant tree species, particularly in selectively harvested forests, potentially increasing water brownification compared to RF forests (Finstad et al. 2016; Škerlep 2021).

The key question in managing forests by CCF is, however, successful natural regeneration. If natural regeneration is not satisfactory, complementary planting or soil preparation of unregenerated patches is needed to establish a sufficiently dense tree stand. The studies published so far indicate promising economic performance for CCF compared to RF both in mineral soil forests and drained peatlands (see

Chap. 8), but those studies assumed satisfactory natural regeneration without any need for complementary activities.

## 14.6 Conclusions

CCF has great potential for reducing the effects of forestry on water quality, both in mineral soil and drained peatland catchments. In particular, CCF is a better alternative to RF because it avoids load-producing practices like DNM and ditch mounding. Although relatively little research has been published to support the performance of CCF from a water quality perspective, the theory behind controlling ground water levels by the ET of the tree stand is strong and the load benefit achieved by avoiding DNM and soil preparation is clear. Implementation of CCF in productive wet peatland forests to mitigate nutrient exports and GHG emissions is becoming widely accepted, and many forest enterprises and the Finnish State now manage those forests exclusively with CCF. The use of CCF as a tool to improve water quality will therefore soon be tested on a large scale.

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