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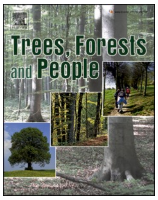

Review Article

Applying continuous-cover forestry on drained boreal peatlands; water regulation, biodiversity, climate benefits and remaining uncertainties[☆]

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A B S T R A C T

Continuous-cover forestry (CCF) is increasingly argued as an alternative to clear-cut harvesting in managed boreal forests to improve water quality and quantity, biodiversity, and carbon sequestration. We review the empirical evidence for the potential benefits of CCF on drained forested peatlands in boreal ecosystems as an alternative to conventional clear-cut harvesting. We also discuss possible risks and uncertainties that need further consideration and highlight unanswered questions that need to be resolved before large-scale implementation. In general, we found that the ability to maintain forest production on drained forested peatlands primarily depends on water regulation of the groundwater (GW) table. Currently, the problem with high GW is typically solved using ditch cleaning, but if CCF is adopted, it could be an alternative approach to manage GW without the need of disturbing this already extensive artificial channel network. Implementation of CCF could lower the risk of extreme flooding and droughts, in addition to maintaining water quality and potentially enhancing the carbon sequestration conditions. Furthermore, it could provide a compromise between industrialized forestry and peatland restoration to better meet these targets. However, several important uncertainties remain regarding the potential for natural regeneration in northern latitudes, the net effect of different types of soil damage due to repeated use of heavy machinery, and consequences of climate change that could result in enhanced storm felling. We primarily focus on Swedish conditions, but also evaluate implications in an international context and propose ways to close remaining knowledge gaps.

Introduction

Production-oriented forestry using even aged, clear-cut harvesting dominates in most boreal regions. Driven by public concern, national legislation, forest certification schemes and new EU directives, improved conservation actions are called for in many countries, especially in regards to improved consideration of freshwater resources, biodiversity and recreation values. In line with this, it is increasingly argued that some form of continuous-cover forestry (CCF) should be used to enhance multiple ecosystem services in production forests while still allowing for the extraction of wood-based commodities (Mårald et al., 2017).

In contrast to even aged, clear-cut harvesting where all trees of a stand are felled at the same time, CCF is a forest management system where only a subset of the trees are extracted while leaving enough individuals for the forest canopy to be maintained at all times (Pommerening and Murphy, 2004; Appelqvist et al., 2021). CCF has a long history of use in Fennoscandia as selective logging, a form of high-grading, was the most common traditional method used across the region until the mid-twentieth century (Östlund et al., 1997), when it became increasingly replaced by clear-cut harvesting methods (Lundmark et al., 2013). In Sweden, CCF was essentially banned in the Forestry Act of 1979 and did not return to the public debate until the update of the Forestry Act in the mid-1990s. In this update, production and environmental considerations where given equal weight, which implicitly lifted the ban on CCF (Stens et al., 2019). Replacing clear-cut harvest with CCF is currently argued for by both national and EU-level politicians (European Commission, 2021), as well as by numerous public actors. Still, CCF remains an uncommon silvicultural practice in Sweden (Mason et al., 2022), and the relatively short open policy window has resulted in limited research on this alternative forest management method (Stens et al., 2019, Hertog et al., 2022, Ekblom et al., 2022). Thus, there is an inherent risk that some of the current debate about CCF being the best forest management direction for the future is driven by ideological reasoning rather than by a sceintific findings.

From a theoretical perspective, there is growing scientific consensus that replacing clear-cut harvesting with CCF could be especially beneficial on drained peatlands where artificial channel networks drained and transformed many wetlands and mires to productive forests about a century ago (Nieminen et al., 2018a, Norstedt et al., 2020, Juutinen et al., 2020). Clear-cut harvesting of these peatlands results in high groundwater levels and wet soils due to the loss of the

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evapotranspiration (ET) capacity when the trees are removed (Sarkkola et al., 2013). The decrease in water lost to ET after harvesting results in additional water in already wet soils that, under current forest management, is typically controlled using ditch cleaning (Sikström and Hökkä, 2016). Ditch cleaning, is a reactivation of historically dug ditches were accumulated sediments and vegetation are physically removed with the goal of improving drainage of the surrounding land. This is an expensive and controversial practice, which often results in increased exports of nutrients and sediments (Nieminen et al., 2018b). The purpose of ditch cleaning is primarily to drain excess water during the period following the clear-cut in order to improve the survivorship of planted tree seedlings (Sikström and Hökkä, 2016). On such areas, CCF has the potential to make ditch cleaning unnecessary by maintaining tree stands with enough ET capacity to keep groundwater levels low and allow regeneration to be successful without disturbing the ditch network (Sarkkola et al., 2013, Nieminen et al., 2018a, Leppä et al., 2020).

Most of the arguments about the positive role of CCF as an alternative management option on forested peatlands are based on research from Finland. Although we can learn tremendously from this work, Finnish drainage history, density, and intensity of ongoing management is different in important ways from Sweden (Hasselquist et al., 2018). Therefore, the purpose of this work is to review the current state-of-knowledge and identify major uncertainties of how CCF on drained peatlands in locations where drainage has not been as industrialized as in Finland could reduce the negative effects of forestry on carbon sequestration, water quality and quantity, and biodiversity. Here we focus on Swedish conditions, but also evaluate this in respect to an international context and propose ways to close remaining knowledge gaps.

The goal of this review is to take a holistic approach to the known and potential benefits, limitations and uncertainties of transitioning from conventional clear-cut forest harvesting to CCF on boreal peatlands. As such, our primary goal is to understand broad patterns in the scientific understanding of how CCF on peatlands could be used to better regulate the hydrology, understand the potential benefits for biodiversity and the climate, as well as assess remaining uncertainties; we will not examine every detail of each of these aspects. With this approach, we hope to communicate our findings to a broad scientific audience, as well as to the surrounding society as a guide to how to direct further research before it can be implemented on larger scale.

What is CCF?

CCF is a group of management methods that maintains an almost intact forest on a given stand over multiple rotations. In Sweden, CCF is often misinterpreted as “high-grading” a form of diameter limit cutting that takes every tree over a certain diameter threshold. This was one of the most common traditional methods used across the region until the mid-twentieth century (Östlund et al., 1997), and led to widespread degradation of Swedish forests. But, other forms of single-tree selection methods could be used that have the potential to restore forests as opposed to degrade them, likely depending on the scale of the harvest.

CCF can be divided into two categories depending on the scale of implementation: single-tree selection cutting and group selection methods (Goude et al., 2022). In Sweden and Finland, the State has defined CCF to include group selection cuts that have an area less that than 0.25 ha, often in so called “checkerboard” pattern or strip-cuts (Appelqvist et al., 2021). While most traditional views do not include such small clear-cuts as CCF, we will include them in our review since they are being applied under this umbrella and their use should be weighed against single-tree selection methods. Hence, such group selection methods could potentially be a compromise to allow for continued use of current forest machinery and make CCF profitable.

The size of the effect of tree harvest on hydrology (and most other environmental consequences) likely depends strongly on the scale of the harvest since each tree is evapotranspiring and therefore affecting the GW level in the surrounding area (Sarkkola et al., 2013). Thus, we hypothesize that the effect increases depending on what type of individual selection cutting method was used (Fig. 1).

Differences in histories of peatland drainage matters

Past government programs encouraged the drainage of peatlands in Sweden starting in the first half of the 1900’s, with the peak around 1933, followed by less intensive drainage until the 1990’s (Paivänen and Hånell, 2012). These efforts have resulted in close to 1 million km of ditches in Sweden (Laudon et al., 2022), and that the country today have amongst the largest area of drained peatland in the world, covering ca 1.5 million ha, or 14% of the productive forest area (Hånell, 1990). Only Finland (~5.4 million ha) and Russia (~4 million ha) have more land area drained, but the Baltic States (~1.5 million ha combined), UK (~0.6 million ha), Norway (~0.4 million ha) and Ireland (~0.3 million ha) have also been substantially affected (Strack, 2008). While these artificial drainage networks in many cases have been successful in terms of forest productivity, it is also one of the most widespread human-induced environmental disturbances in many countries with largely unknown, but potentially large, legacy effects on waters, biodiversity, and soil carbon (Lõhmus, et al., 2015; Nieminen et al., 2018c; Koschorreck, et al., 2020).

Most drainage ditches in Sweden where dug by hand, are relatively shallow and often occur in the bottom of swales in irregular patterns, draining zero-order basins or groundwater discharge areas (Hasselquist et al., 2018). In contrast, ditch networks in Finland are typically standardized with a central channel that collects water from numerous parallel ditches 20 - 40 m apart. These Finnish drainage networks were primarily dug with machines from the 1950’s through the 1990’s (Paivänen and Hånell, 2012) and lend themselves to an industrialized maintenance scheme with their ordered, fish-bone like arrangement. In Finland, ditch network maintenance (DNM) or ditch cleaning is a standard and government subsidized procedure, typically repeated every 20–40 years with the goal of sustaining the desired drainage effect (Sikström and Hökkä, 2016). Compared to Finland, where the entire ditch network usually is cleaned regularly, ditch cleaning in Sweden primarily focuses on the period immediately following final felling and seldom includes the entire original channel network. Furthermore, while Swedish legislation only allows cleaning of already existing ditches, and only down to the original channel depth, Finnish rules do not specify any maximum depth and can add “complementary ditches” between existing ones (Sikström and Hökkä, 2016). All this to say, the drainage history, density, and intensity of ongoing management is different in important ways between Finland and Sweden, and we need to consider this when interpreting how results from studies in Finland could translate to management of Swedish drainage systems.

Potential for regulation of groundwater using CCF

In peatlands, the GW level is the most central feature regulating hydrological processes, carbon sequestration, vegetation type, and forest productivity. GW level is controlled by the water balance at the site, i.e. the balance between precipitation input, ET losses back to the atmosphere and the drainage potential (channel density, slope and hydrological conductivity of the soil). In turn, this determines the oxygen content of the soil, affecting redox conditions and thus, has fundamental ecological and biogeochemical implications (Ledesma et al., 2018; Blackburn et al., 2017). As such, the depth of the GW level also regulates root depth and therefore has important consequences for the vegetation composition as well as the productivity of trees (Hånell, 1988). The GW level also controls peat decomposition and greenhouse gas (GHG) production and emissions (Evans et al., 2021; Minkkinen et al., 2020; Turetsky et al., 2014).

Using CCF as a means for regulating GW as an alternative to ditch cleaning has been proposed as advantageous when considering both

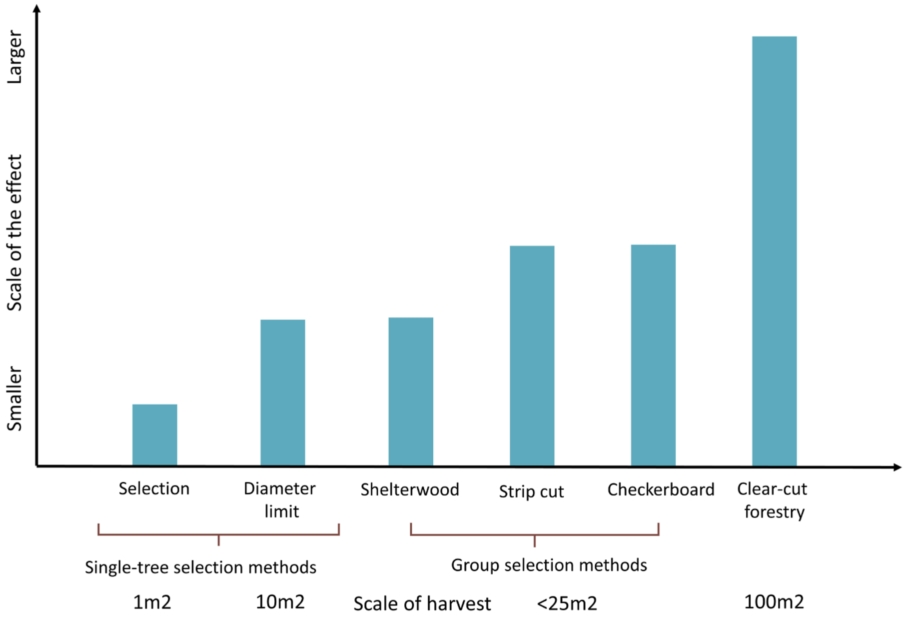

Fig. 1. List of different methods of continuous cover forestry (CCF) methods considered in this article ranked on the x-axis by the scale of the harvest from single-tree up to larger group selection methods that are under 0.25 ha, along with clear-cut forestry for comparison. Each management method was assigned a hypothesized scale of the effect on various ecosystem properties based on the literature.

environmental and economic perspectives in Finland (Nieminen et al., 2018a; Juutinen et al., 2021). The theoretical basis for this is that the remaining trees and field-layer vegetation can maintain the ET capacity so that the GW level is kept low enough for the new tree seedlings to survive (Leppä et al., 2020). However, using CCF to regulate GW requires in-depth understanding of the hydrological functioning of the peatland and a mechanistic link between the different ET components of vegetation, which includes transpiration and interception-evaporation processes of both trees and understory species (Launiainen et al., 2016; Fig 2). Retaining enough trees and field-layer vegetation for the ET processes to balance the increased need for drainage when a portion of the tree stand is harvested is hence key for successfully implementing CCF as an alternative to ditch cleaning in drained peatland forests.

Studies conducted in Finland and Canada on group selection methods have tested how different levels of thinning or strip cutting can affect GW levels in a boreal context. Most recently, Roy Proulx et al. (2021) found that partial harvest of 40% of the basal area in a black spruce stand in Canada did not influence the GW level one year following treatment. Leppä et al. (2020) demonstrated that removing up to 70% of the stand basal area in Norway spruce dominated sites in Finland only marginally affected the GW level, and hence eliminated the need for ditch cleaning. They postulated that the limited GW level

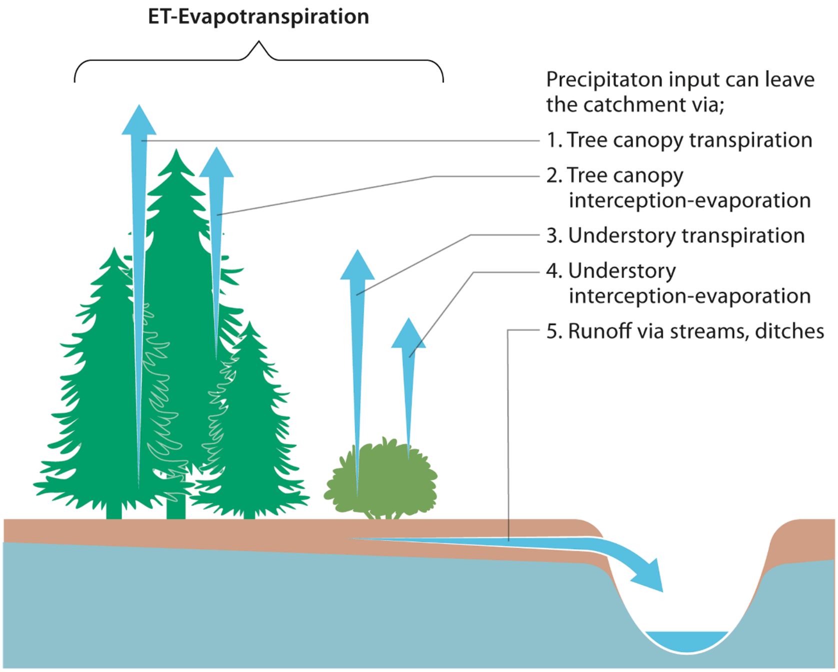

Fig. 2. Pathways of water loss in a drained forest that affect the water balance, and thus groundwater (GW) level of the site. Management of the tree canopy with CCF could thus reduce the need for ditch cleaning. Water input to peatland comes from both direct precipitation and from lateral input from the surrounding areas.

response was due to a rapid establishment of field layer vegetation that largely counteracted the canopy loss effect (Fig. 2). So while the tree canopy in mature stands is the most important component for water loss through ET, more light and nutrient availability after tree harvesting can stimulate understory growth and maintain ET capacity (Leppä et al., 2020). Pothier et al (2003) found that cutting 50-60% of the basal area in a red spruce-balsam fir dominated sites induced the best regeneration response of the vegetation and, thus, recovery of the GW level compared with clear-cutting effects. (Päivanen and Sarkkola, 2000) found that removal of 30% of the stand had no significant effect on GW levels, making DNM unnecessary. Furthermore, a number of older studies had similar conclusions on partially harvested sites (Heikurainen, 1966, Heikurainen and Päivänen, 1970, Päiveänen, 1970, Päivänen, 1980, Hökkä and Penttilä, 1995). In a more recent study from Finland, GW level of strip cuts of different widths were monitored and modelled and found that this type of group selection harvest or partial harvesting can keep GW levels lower than a clear-cut, but depended on the conductivity of the soil and stand density (Stenberg et al., 2022). These narrow strip cuts kept GW level the lowest, but in general, strip cutting was not as effective at controlling GW level as single-tree selective harvesting (Stenberg et al., 2022). While most traditional views do not include strip cuts as CCF, definitions of CCF in both Sweden and Finland consider these small harvests under the umbrella of CCF or 'clear-cut free forestry' (i.e. "hyggesfritt" in Swedish) if the area is under 0.25 ha. They could potentially be a compromise to allow for continued use of conventional forest machinery and make CCF profitable. While it is clear that CCF can control GW levels in many contexts in a variety of tree stand types, variation within studies depended on peat types. Hence, it needs further testing in other geographic locations and physical settings and improved modeling capability before it can be widely accepted that CCF is the best way of managing GW across all drained forested peatlands.

Carbon perspective

Boreal peatlands is one of the largest terrestrial carbon pools globally (Bradshaw and Warkentin, 2015). The mechanism behind this large build-up of soil organic matter (SOM) in this northern biome is primarily due to the water balance (Frolking et al., 2010); flat topography and poor hydrological drainage combined with low ET capacity due to low temperatures results in high GW levels that leads to reducing conditions and slow SOM decompositions rates. Hence, despite generally low biomass production of most pristine boreal peatlands - primarily through the growth of sphagnum moss and sedges - plant detritus accumulation has been ongoing since the last glaciation and resulted in a carbon storage pool of global significance (Ovenden, 1990).

Historical ditching, along with the establishment and growth of productive forest with higher ET capacity has, however, lowered GW levels in many peatlands, and led to peat subsidence and enhanced SOM mineralization rates (Fig. 3). Estimates of peat subsidence due to peatland drainage can, in extreme cases, result in up to 1 cm vertical loss per year in boreal peatlands (Simola et al., 2012; Oleszczuk et al., 2021), especially close to ditches where the GW drawdown is the largest. However, peat subsidence related to drainage does not always result in a proportional net loss of SOM. This is because the removal of water also leads to peat compaction, and that the C loss, at least partly, becomes counteracted by increased net primary production, litter fall and fine root production (Minkkinen and Laine, 1998), and hence may not necessarily mean that ditch cleaning has a negative impact on the greenhouse gas balance (Tong et al., 2022). This raises the question, does drainage to support forest growth result in a long-term net sink or net source of C?

In a recent circumboreal assessment of the role of forest management for the carbon balance, Högberg et al. (2022) concluded that active forestry promotes the sequestration of SOM in general, but that drained peatlands are questionable in this context because of enhanced GHG emissions. In Finland, Korkiakoski et al. (2019, 2020) showed that at least part of those enhanced GHG emissions can be counteracted by using CCF, instead of clear-cutting practices. Because the soil C balance depends not only on the rate of decomposition but also on the input of new organic matter, all components need to be considered when estimating the performance of CCF as an alternative to conventional harvesting methods. Although not empirically tested, the input to the SOM pool has been suggested to be more consistent over time in a forest

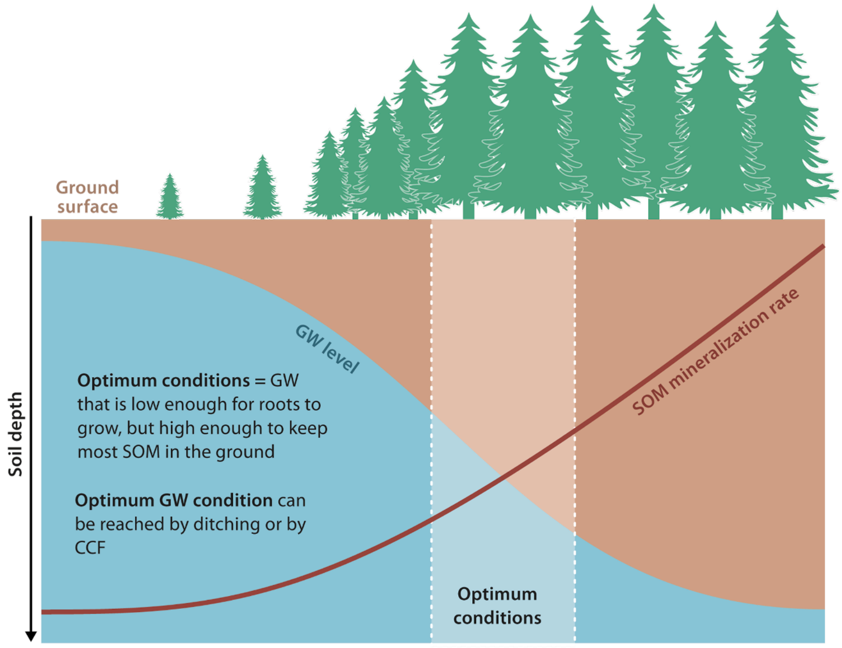

Fig. 3. Conceptual model of the relationship between groundwater (GW) level and soil organic matter (SOM) mineralization rate (not to scale). The optimum conditions for the GW can be achieved through ditch cleaning after clear-cut harvesting, or by using CCF methods to maintain evapotranspiration (ET), and thus, the GW level.

managed with CCF compared to even-aged managed forests because the time of low C inputs immediately after clear-cut can be avoided (Nieminen et al., 2018a).

Compared to CO_2, other GHGs such as CH_4 and N_2O have received much less attention in the study of forest management on drained peatlands. Consequently, only a few studies have included all three major GHG components (see Ojanen et al., 2010). While the drainage impact on N_2O is more dependent on peatland fertility, CH_4 is strongly related to high GW levels (Minkkinen et al., 2020). In a Swedish context, most of the fertile peatland soils occur in the southern part of the country, whereas most of the north is dominated by nutrient poor peatlands. From a GHG balance perspective, the risk of N_2O emissions is especially high in southern peatlands previously used for agricultural purposes where the GW levels are especially important to regulate for optimum conditions (Kasimir et al., 2018). The future fate of peatland GHG balance will also depend on how the water balance is affected by climate warming. Although little is known about the amount and timing of precipitation in a future climate, the ongoing warming trend will likely result in an enhanced rate of ET, a pattern that already has been observed in the north (Laudon et al., 2021). Therefore, the current use of ditch cleaning as a tool to stimulate tree growth, could reduce survival rates of tree seedlings because of predicted enhanced drought conditions in the region. As such, CCF can potentially be an effective tool to counteract the negative consequences associated with ditch cleaning on the SOM pool in forested peatlands, allow for relatively high tree growth, and provide a less risky hydrological future for peatland forestry.

Hydrological context

One important environmental benefit of successful implementation of CCF on peatlands as an alternative to even-aged, clear-cut management is that ditch cleaning would no longer be needed to regulate GW levels. Even though ditches are an extension of the natural stream network in how they drain water, solutes and contribute to aquatic biodiversity, they have very little legal consideration in Sweden. In fact, landowners only need to notify the Swedish Forest Agency of ditch cleaning operations if *they believe* that there will be downstream consequences for water quality (Andersson et al., 2016). This is in contrast to natural streams that are legally protected from physical disturbance and require forested buffer zones surrounding them to provide shading and protect water quality from the effects of the adjacent clear-cut (Andersson et al., 2016). Human dug ditches that feed these streams, and even modified streams that may now look like ditches because they were straightened to increase drainage capacity, require no protective buffer zone (Kuglerova et al., 2017). In practice, this means that large excavators can drive in and around the capillaries of the boreal landscape as they remove accumulated sediments and vegetation in ditches without any effective remediation options in place (Haahti et al., 2017). This is allowed despite potentially devastating downstream consequences when sediments and nutrients are exposed and then transported during the cleaning process (Fig 4; Marttila and Kløve, 2010; Nieminen et al., 2017). As a comparison, in the downstream natural stream no machinery is allowed within 10 m from the water.

Of all the forested channels in Sweden that are less than 6 m wide, 67% have been constructed by humans (Flyckt et al., 2022). These drainage systems allow water to leave the catchment much more rapidly because channelized flow rates are several orders of magnitude faster

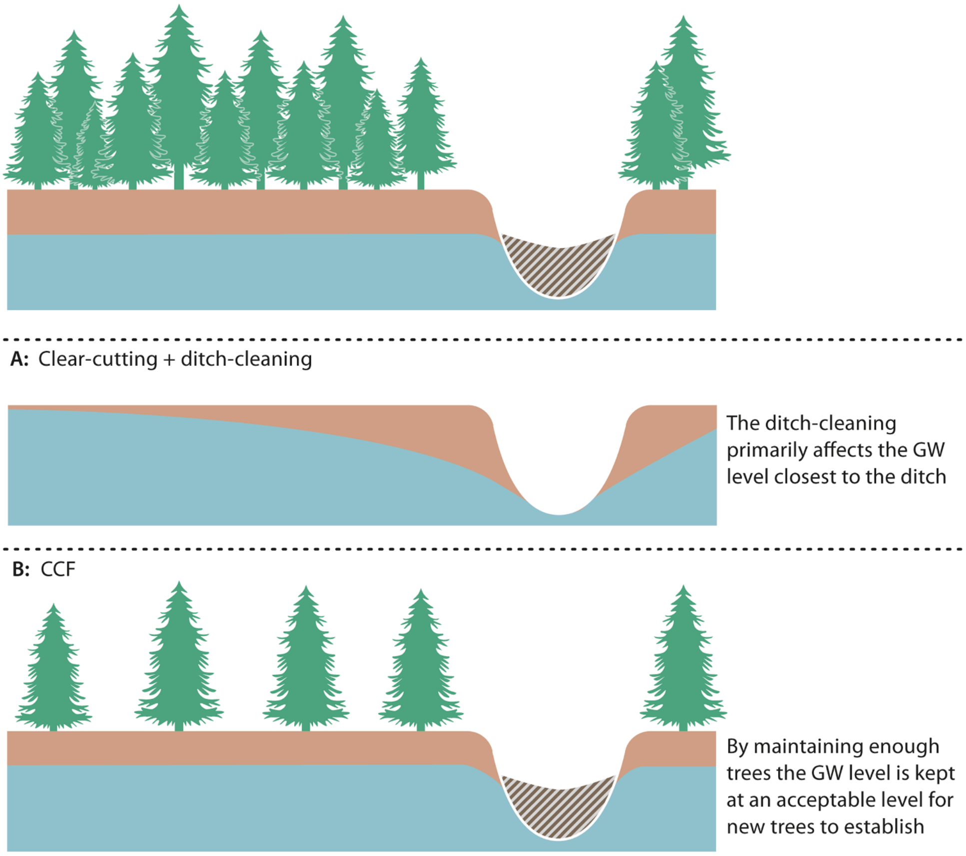

Fig. 4. Illustration of the effects of forest management options on groundwater levels for continued management of peatland forests for wood and biomass production. The condition of the mature drained forest is shown in the top panel, while panels (A) and (B) below show conditions with different management options (A) traditional clear-cutting followed by ditch cleaning and (B) continuous cover forestry (CCF) without ditch cleaning.

than that of matrix and macropore flow through soils of pristine peatlands (Rawls et al., 1993). Lowering of GW levels using drainage ditches leading to peat subsidence and increased bulk density also results in decreasing hydraulic conductivity (Silins and Rothwell, 1998; Price et al., 2003). In fact, peat subsidence seems to be the most important factor that cause ditches to become shallower over time (Heikurainen, 1957). Subsidence in combination with sediment infilling and vegetation growth in the channels are hence a main reason for the need of repeated ditch cleaning necessary for even-aged forestry practice to be possible on wet soils (Päivänen and Hånell, 2012).

The GW level response to artificial drainage is largest close to the channel, and decreases exponentially with increasing distance to the ditch. In a meta-analysis, Bring et al. (In press) found that GW levels were lowered by an average of ~30 cm adjacent to the ditch, is then halved 10 m away, and lost almost entirely ~30 m from the channel. Variability in the hydrological conductivity of the peat is a main factor determining the rate of reduced drainage effect with distance to the ditch (Laurén et al, 2021). In turn, this means that the decreasing hydrological conductivity over time due to peat subsidence reduces the effect of repeated drainage (Meseret et al., 2022). Consequently, the efficiency of ditch cleaning will become less effective each time it is repeated, and can in some cases be lost altogether after just a couple of rotations.

Enhanced hydrological sensitivity to extreme events is yet another potential consequence of ditch cleaning. Water storage and release are regulated by the architecture of the landscape, and hence related to topography, hydrological conductivity and channel density (Jencso and McGlynn, 2011). The water storage potential and release rates determine if downstream areas will be flooded during extreme precipitation events, if streams will dry out during drought and for how long memory effects of previous events will persist. Peatlands, and their drainage status, are central in this context as they store and release water differently depending on their land-use history. Artificial drainage has large effects on dynamic water storage, which is a central feature for providing consistent water to streams and regulating runoff processes (Staudinger et al., 2017). In boreal regions, peatlands are areas with very large total water storage, but with small dynamic storage, meaning that only a small fraction of the large water amount is available for stream runoff, making them especially prone to disturbance (Karimi et al., 2022). Consequently, ditch cleaning should result in more flashy hydrographs and as such cause both higher peak flows during floods and lower baseflows during droughts (Prevost et al., 1999, Menberu et al., 2016). Hence, while the effect of the historical peatland drainage may be on a trajectory towards more natural conditions in Sweden through passive restoration, ditch cleaning reactivates the hydrological disturbance and makes the landscape more prone to negative effects from future extreme climate conditions. Such negative effects will likely not only affect the water quantity, but also the quality of surface waters in the boreal region (Tiwari et al., 2022).

Water quality framework

Peatlands play a major role in regulating water quality in the boreal landscape. High concentrations of dissolved organic carbon (DOC) and dissolved inorganic carbon (DIC) are defining features of streams draining these large carbon-storing features (Gomez et al., 2021). In fact, stream export of DOC and DIC combined can be substantial – and even turn peatlands from an apparent carbon sink to a carbon source as the climate becomes warmer (Nilsson et al., 2008). Furthermore, the legacy of peatland drainage has demonstrated that the extent of the ditch network is an important reason for the increase in stream water DOC - called “brownification” (Asmala et al., 2019; Nieminen et al., 2021).

Similarly, dissolved inorganic nitrogen (DIN), especially ammonium, can be much higher from peatlands than from catchments draining adjacent forests (Sponseller et al., 2016). Furthermore, the export of contaminants originating from anthropogenic deposition can be tenfold higher from peatlands compared to forested catchments, whereas elements originating from natural weathering processes often are up to tenfold lower (Lidman et al., 2014). This heterogeneity in responses makes peatlands one of the most important features regulating water quality at the landscape scale, but also suggests that perturbation of these areas can cause disproportionate large downstream consequences (Laudon and Sponseller, 2018).

During ditch cleaning, increased sediment transport can pose serious water quality issues, both directly through increased sediment loads (Marttila and Kløve, 2010) but also indirectly through co-transport of nutrients and other solutes (Nieminen et al., 2017). It is well known that suspended sediments can destroy downstream aquatic habitats, smother spawning beds, cause loss of fish populations, and severely alter the abundance and biodiversity of aquatic invertebrates (Annala et al., 2014; Kjelland et al., 2015). While sediment pollution often affects local downstream areas, these effects can be long lasting as it often takes many years to several decades for habitats to be re-colonized and recover. In fact, sediment erosion, transport and re-deposition has been identified as one of the most serious, but still most under-studied water quality aspect in Sweden (Futter et al., 2016).

In addition to avoiding the negative effects of ditch cleaning listed above by using CCF, another type of soil disturbance could be avoided in some cases, namely site preparation through soil scarification (exposing mineral soil into which seedlings are planted). This does require that implementation of CCF results in successful natural regeneration, instead of planting seedlings that is normally required in the Swedish forestry context. From a water quality perspective, soil scarification is often done using disc-trenching and is considered one of the most detrimental aspects of even-aged forestry as it has been found to lead to enhanced DOC export (Schelker et al., 2012) and raised levels of methylmercury (Eklöf et al., 2014). Reducing the need for soil scarification could also have other positive effects on, for example, the recreational value and biodiversity as it is one of main physical disturbances to the site.

Biodiversity

Northern peatlands host unique and specialized vegetation, birds, and insects with some species exclusively found in these wet and carbon-rich areas. Because of this unique biodiversity that stands in stark contrast to the dominating forested ecosystems, peatlands are of fundamental importance for the regional biodiversity. However, artificial drainage resulting in the establishment of productive primary forest has resulted in significant impacts on peatland habitats, both quantitatively and qualitatively (Vasander et al., 1997). Trees, primarily Norway spruce (*Picea abies*), and common, sub-canopy and shade tolerant species have established and now dominate on many peatlands at the expense of specialized wetland plants. While there are close functional linkages between plants, water and peat, many other aspects of biodiversity, including birds, invertebrates, fish, fungi, lichens, etc., have likely also been heavily affected by artificial peatland drainage and the increased dominance of spruce (Remm et al., 2013, Rosenvald et al., 2014, Lõhmus et al., 2015).

How CCF can be used as a means to reduce negative drainage effects of peatland biodiversity remains uncertain. While empirical evidence largely are lacking, model results support the notion that CCF could be beneficial for biodiversity generally in the forest landscape (Eyvindson et al., 2021; Gustafsson et al., 2012). While CCF likely will have only marginal effects on restoring peatland biodiversity to its pristine condition, Hannerz and Hånell (1993) have shown that shelterwood harvest is better at preserving the plant biodiversity on historically drained and productive peatlands dominated by Norway spruce compared to using conventional clear-cut harvesting methods. This was especially so for species preferring shaded and moist conditions, whereas those needing high levels of nitrogen increased when using conventional clear-cut methods (Hannerz and Hånell, 1997). While there are several remaining uncertainties about how CCF can enhance biodiversity on peatlands, it can provide a compromise between industrialized forestry and peatland restoration to better meet biodiversity targets.

Potential risks of using CCF on peatlands

While we have described a number of potential positive aspects of applying CCF on peatlands, possible risks also need consideration. Perhaps most importantly, unanswered questions need to be resolved before society should promote large-scale implementation of CCF on peatlands in Sweden. The risk of driving damages is one such aspect; shorter interval times between the uses of off-road heavy forestry machinery that can harvest large trees could increase the occurrence of driving damages. Peatlands are among the most sensitive land areas for rutting that cause channelization of water, hotspots for methylmercury production and enhance erosion problems (Eklöf et al., 2014). Peatlands are more sensitive than other boreal soils because of their low bearing capacity (Ågren et al., 2014), and during clear-cut management, rutting is often avoided by harvesting these areas in winter when the soil is frozen. But, as winters are getting warmer and soil frost is predicted to decrease in duration and extent (Oni et al., 2017), depending on cold winters in the future will likely not be a successful approach. Furthermore, branches and stems of less profitable trees are typically used to enforce haul roads and protect the soil from rutting and compaction in conventional clear-cut harvesting (Andersson et al., 2016), which in a CCF context will not be possible to the same extent as these less profitable trees will be saved standing until later selective harvest operations.

Once drained, many productive peatlands in Sweden have transitioned from sparse slow growing Scots pine (*Pinus sylvestris*) to Norway spruce dominated, often because of an active, economically based decision by the landowner. Norway spruce is a secondary species that is more shade tolerant compared to the other common tree species native to Sweden, Scots pine and downy birch (*Betula pubescens*) that need direct sunlight and typically establish after fire, storm felling and/or clear-cutting. This suggests that implementation of CCF will likely result in most drained peatlands becoming even more spruce dominated, as other native species will not regenerate naturally. Enhanced dominance of spruce is not necessarily beneficial for water quality on a local or regional scale as there are clear connections between increased spruce dominance and surface water brownification in Sweden (Kritzberg, 2017, Skerlep et al., 2020). Because brownification has a negative impact on the quality, ecology and esthetic values of surface waters (Kritzberg et al., 2020), active management is now needed to enhance the species diversity around streams to better protect water quality (Hasselquist et al., 2021).

Unless regeneration issues are solved, the increased dominance of Norway spruce in peatlands managed with CCF will likely increase the susceptibility of forests to climate change related effects (Fig 5). Norway spruce is particularly sensitive to heat and drought, due to its shallow root system and, therefore, likely affected by global warming conditions (Lopez et al., 2021). Enhanced wind throw is another potential threat in the future climate where more extreme storms are expected (SMHI, 2019). In a Swedish shelterwood study, within 6 years after a partial harvest, ca 40% of the trees had blown down (Hånell and Ottosson-Löfvenius, 1994). While wind throw of trees is a relatively common phenomenon when using various thinning strategies because of lack of support from neighboring trees, spruce are particularly sensitive to wind throw because of their root structure (Felton et al., et al., 2016), especially on moist peat soil that provides little physical soil support for the tree roots. While it is well established that wind throw results in more deadwood, large rootwads from the shallow root systems cause large erosion potential and water quality degeneration that can be detrimental to streams (Kuglerova et al., 2021).

Unanswered questions and need for further research

Although the use of CCF as an alternative to ditch cleaning for maintaining GW levels seems promising from many perspectives, our review suggests that several issues remain to be tested before it safely can be implemented at larger scales. These uncertainties range from hydrological mechanisms to consequences of climate change, as well as the best way to avoid driving damages with repeated entry to wet sites. While the remaining uncertainties listed below are primarily based on local effects, one additional aspect to consider is what the cumulative large-scale consequences would be if CCF would become the main forest management in the future.

Hydrological consequence of CCF not fully resolved. Although the use of CCF on forested, productive peatlands is motivated by its ability to maintain GW at levels that could make ditch cleaning unnecessary, several important hydrological questions remain unanswered. First,

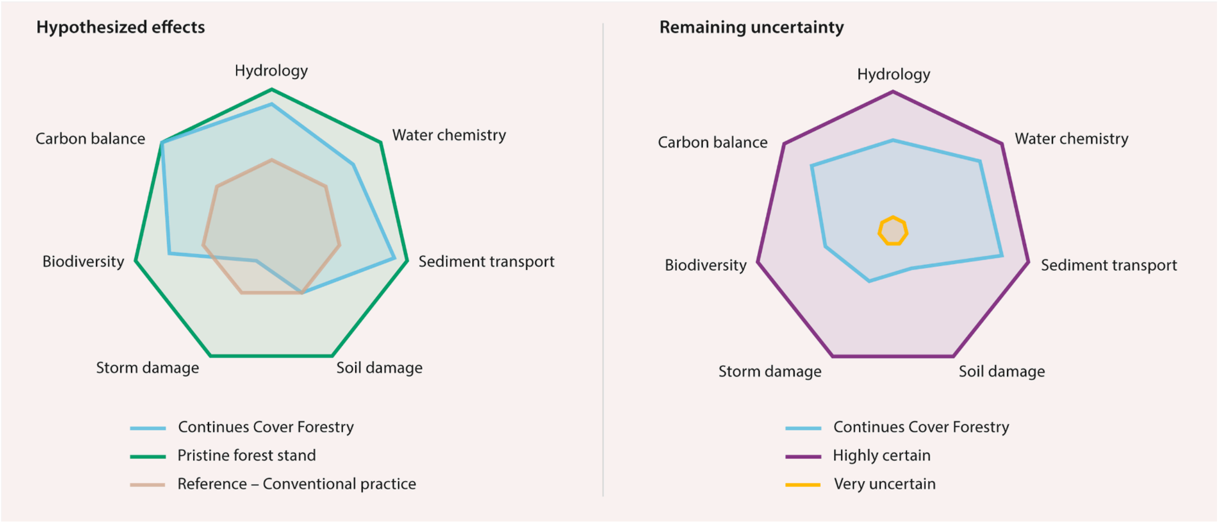

Fig. 5. Hypothesized effects (left panel) and remaining uncertainty (right panel) of the benefits of CCF on drained peatlands based on the literature included in this study. Left panel – benefits of peatland CCF (in blue) relative to conventional forest management including clear-cut harvesting and ditch-cleaning (orange) and to pristine peatland forest stands (green). Left panel – the level of uncertainty about the benefits of peatland CCF for each of the factors, where purple is highly certain and red is highly uncertain. Note that the scales are relative and that the results are the subjective view of the authors.

what proportion of the tree canopy must be left unharvested for regulation of the GW table to be successful at a range of climates? As mentioned above, GW levels are regulated by the balance between precipitation inputs and what is lost back to the atmosphere through ET, and lateral drainage via ditches and streams. But, the lateral drainage via ditches and streams is highly variable, both spatially and temporally, and driven by landscape and soil properties. Although some work has been conducted in Finland as discussed above (Leppä et al., 2020), published tests have primarily been done using strip cutting (Stenberg et al., 2022) and/or small openings (<0.25 ha), which do not qualify as clear-cuts, but also are not what has been traditionally seen as CCF. Either way, more empirical studies of different selective harvesting methods, across various geographic settings are needed in order to evaluate the effects on GW levels.

GHG and CCF: Although it seems that CCF from a C perspective could be more beneficial compared to conventional harvesting methods on forested, productive drained peatlands, additional studies remain to be conducted in order to close remaining knowledge gaps. While this is certainly true for CO_2, it is at least equally important to also include other GHG components such as CH_4 and N_2O into this future perspective. From a theoretical perspective, CCF has the potential to decrease C emissions from peat soils by constantly maintaining GW levels sufficiently deep to allow tree growth, but not so deep that it results in accelerating organic carbon mineralization (Fig. 3). Again, such argumentation has been supported in Finnish studies using strip-cutting (See Nieminen et al., 2018a, Stenberg et al., 2022). However, the extent to which this potential could be realized in other CCF peatland forest contexts dominated by shallower ditch depths and irregular and wider spacing – as found in Sweden - has not been properly tested.

Natural regeneration - a prerequisite for CCF: Large scale, low environmental impact implementation of CCF requires that natural regeneration of seedlings is successful (Erefur, 2011). While this has been shown in many places at more southern latitudes, the soil and climatic circumstances of northern latitudes have shown that regeneration is poor without natural disturbance (Lundqvist, 2017). In even aged, clear-cut forest management in Sweden, soil scarification with high mounding or disk trenching, followed by planting is the common management practice. It has been suggested that natural regeneration requires soil disturbance, either natural or artificial, because of a nutrient lock-in effect on nutrient poor northern soils (Högberg et al., 2021). How this can be translated to peatlands will require further research, but at least one study from Sweden suggested that the height development of spruce seedlings without soil disturbance is slower, resulting in two to three times longer regeneration times (up to 20 years) compared to conventional soil scarification and planting alternatives (Holgén and Hånell, 2000).

Biodiversity consequences of CCF: While CCF in traditional forest stands is usually believed to enhance the biodiversity of flora and fauna (Kuuluvainen et al., 2012), the consequences of CCF management of drained peatlands are less certain. Even when the primary goal has been to restore the hydrological conditions of drained peatlands, returning the plant species diversity to a natural, pre-drainage state is more difficult (Kreyling et al., 2021). Given this difficulty, implementation of CCF on productive, forested peatlands will not restore species composition and biodiversity to a pre-drainage state, but could at least maintain higher plant species diversity compared with even-aged, clear-cut forest management (Hannerz and Hånell, 1993, 1997). Furthermore, other factors besides drainage are more important for preserving red-listed species in natural wet forests, namely deadwood, which is reduced in any type of managed forest (Hannerz and Hånell, 1997). Thus, it is uncertain if applying CCF on productive, forested peatlands would achieve goals for returning biodiversity towards more natural pre-drained peatland conditions – but could at least reduce the impact of forestry on biodiversity in general.

CCF on peatlands in a climate change perspective: The effect of more frequent extreme weather events in a future climate – particularly on peatland forestry - is not well understood. Climate change will likely create a higher risk of storm felling, severe droughts and flooding, especially because of the shallow root systems of the dominant Norway spruce (Felton et al., 2016). CCF could alleviate mortality via drought and other issues under some circumstances and could make peatland forests more resilient in the face of climate change. But, a more thorough risk assessment is needed because of the long forest rotation periods in northern latitudes.

Practical implementation of CCF on peatlands: CCF in a modern, mechanized forestry context will increase the need for off-road driving. In even-aged, clear-cut management, heavy machines are only used in the last phases of management (commercial thinning and final felling), giving the soil some 50 years to recover in the boreal forest. Using CCF, it is possible that heavy machines would be needed to remove trees every 20 years, which could be problematic since soil compaction and driving damages have the potential to increase with repeated machine passes (Labelle et al., 2022). In general, soil disturbance will likely be reduced by using CCF, because the need for soil scarification and ditch cleaning can be avoided, but it is still unclear to what extent the combined effect of these changes in management will be on the exports of water, sediment, nutrient, carbon, metal and mercury (Nieminen et al., 2018).

Concluding remarks

To meet the requirements set by international and EU forest policies as well as address increased public concern about the negative effects of forestry, Sweden will likely have to increase the use of alternatives to the current even-aged management strategies through the incorporation of more CCF. Although ecological restoration of peatlands should be a priority in places where historical ditching had no effect on forest growth, many peatlands have been drained to become highly productive forests. Implementing CCF on these productive drained peatlands is likely the best option for expanding the use of CCF in Sweden because continuous tree cover can manage the groundwater level, cause less soil disturbance, as well as reduces costs when ditch cleaning and soil scarification are avoided. The cascading effects of this water level management will likely also positively influence the GHG and carbon budget, water quality and quantity, biodiversity, etc. (Fig. 5). Thus, CCF could provide a compromise between industrialized forestry and peatland restoration to better meet these targets. Furthermore, in the face of future uncertainties, diversifying forest management in Sweden with practices such as CCF could be used as a potential ‘insurance policy’ to spread the risks of damages that could become more frequent and intense with climate change. However, widespread implementation of CCF on drained peatlands should be approached with caution and primarily done experimentally until more empirical studies have been done to close existing knowledge gaps and evaluate major risks.

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Declaration of Competing Interest

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Data availability

No data was used for the research described in the article.

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