Could continuous cover forestry be an economically and environmentally feasible management option on drained boreal peatlands?

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Abstract

Environmental and economic performance of forestry on drained peatlands was reviewed to consider whether continuous cover forestry (CCF) could be a feasible alternative to even-aged management (EM). CCF was regarded feasible particularly because continuously maintaining a tree stand with significant transpiration and interception capacity would decrease the need for ditch network maintenance. Managing CCF forests in such a way that the ground water levels are lower than in clear-cut EM forests but higher than in mature EM forests could decrease greenhouse gas emissions and negative water quality impacts caused both by anoxic redox reactions and oxidation and mineralization of deep peat layers. Regeneration studies indicated potential for satisfactory natural regeneration under CCF on drained peatlands. An economic advantage in CCF over EM is that fewer investments are needed to establish the forest stand and sustain its growth. Thus, even if the growth of trees in CCF forests were lower than in EM forests, CCF could at least in some peatland sites turn out to be a more profitable forest management regime. An advantage of CCF from the viewpoint of socially optimal forest management is that it plausibly reduces the negative externalities of management compared to EM. We propose that future research in drained peatland forests should focus on assessing the economic and environmental feasibility of CCF.

Key words: Forest economics; GHG fluxes; regeneration; silviculture; tree growth; water quality

1. Introduction

Peatlands are the most common type of wetlands globally (Joosten and Clarke 2002) and provide ecosystem services such as timber production, climate regulation, water quality control, flood abatement, biodiversity conservation, as well as recreational benefits (Zedler and Kercher 2005, Tolvanen et al. 2013). Drainage for forestry, agriculture and peat extraction compromise the multiple ecosystem services, which these peatlands provide in their pristine state (Chapman et al. 2003, Čížková et al. 2013, Bonn et al. 2016). However, little attention has been devoted to analysing economically and environmentally optimal forest management alternatives on peatlands.

Altogether, around 15 Mha of peatlands have been drained for forestry in the boreal and temperate zones, providing an economically important source of woody biomass (Paavilainen and Päivänen 1995).
In Finland, for example, drained peatlands are an integral part of operational forestry, covering about 25% (4.7 Mha) of the total forest land area. Large areas of peatlands have also been drained for forestry elsewhere in the boreal region, e.g., 3.8 Mha in Russia, 1.4 Mha in Sweden, and 0.5 Mha in Estonia.

Thus far, even-aged management (EM) has been the prevailing management principle in drained peatland forests. The purpose of forest management in EM is to achieve a nearly coeval cohort of trees and eventually harvest and regenerate the forest by clear-cutting followed by soil preparation and planting or seeding, rarely using natural regeneration with seed-trees. In the Nordic conditions, EM further involves intermediate thinnings from below to improve the growth and vitality of the remaining dominant trees. Ditch network maintenance (DNM) operations are recommended every 20-40 years to sustain and improve drainage conditions (Sikström and Hökkä 2016). After clear-cutting, some type of soil preparation in conjunction with DNM, e.g., ditch-mounding, is considered necessary to establish a new tree stand and lower the ground water table (GWT) that is temporarily raised by harvesting the tree stand with significant evapotranspiration capacity (Heikurainen and Päivänen 1970, Päivänen 1982, Lundin 2000).

A problem in EM on drained peatlands from the economic viewpoint is that major investments are needed to establish the forest stand and sustain its growth. Soil preparation, artificial regeneration, DNM and pre-commercial thinning each incur expenses, which can only be compensated for by the incomes from forest harvestings. From the environmental viewpoint, problems are caused particularly by sediment, nutrient and carbon release to receiving water bodies after DNM (Joensuu et al. 1999, Nieminen et al. 2010) and clear-cuts (Rodgers et al. 2010, Kaila et al. 2014, 2015, Nieminen et al. 2015). A number of options have been proposed to manage water quality after DNM (Haahti et al. 2018, Nieminen et al. 2017b) and clear-cut (Nieminen et al. 2017a). While not necessarily efficient in managing water quality, different water protection structures inevitably further increase the costs of timber production on drained peatlands.

An environmental problem in EM on drained peatlands is also that carbon dioxide (CO_2) emissions from soil may be so high that the drained sites become net sources of CO_2 to the atmosphere, unlike in pristine peatlands and upland forests. This may be the case particularly in the most nitrogen rich sites, and in highly-stocked stands with mature trees, as their transpiration demand results in a low GWT and aerobic decomposition in deep peat layers (Ojanen et al. 2010, 2013).

Since EM has detrimental impacts on several ecosystem services provided by peatlands, and is less profitable on peatlands (Kojola et al. 2012) than in uplands (e.g., Hynynen et al. 2015), the demand for alternative management options, such as continuous cover forestry (CCF), has increased. CCF can have potential on drained peatlands because continuously maintaining a tree stand with significant transpiration and interception capacity could decrease the need for DNM (Sarkkola et al. 2010, 2013). Futhermore, natural regeneration, a crucial factor for successful implementation of CCF, could be a feasible option particularly on peatlands, where ample soil moisture and the occurrence of *Sphagnum* favor seedling germination (Place 1955, Heinselman 1957, Wood and Jeglum 1984) and establishment. Several studies conducted in the Nordic countries have shown successful natural regeneration in spruce mire sites after partial cutting (Lukkala 1946, Hånell 1993, Holgen and Hånell 2000, Örlander and Karlson 2000)

Except for the studies researching natural regeneration success in small canopy gaps (Hökkä et al. 2011, 2012, Hökkä and Mäkelä 2014), no attempts have been made to study the feasibility of specifically CCF on drained boreal peatlands. By conducting a literature review our aim was to raise the question whether CCF has potential as an economically, environmentally, and socially feasible management option on drained peatlands.

The applied definition for CCF in our review is relatively broad, i.e., all management options which do not aim for an even-aged stand structure, are based on natural regeneration, and retain a significant proportion of the tree stand after harvesting, are considered as CCF. Thus, executing clear-cuts in small patches or narrow strips of trees is considered CCF as long as the purpose is to keep most of the area continuously canopy-covered and artificial regeneration is not applied. Retaining significant proportion of the tree stand after harvesting is particularly important as we hypothesize that such management can significantly decrease the need for DNM. Although strict limits cannot be given to distinguish the tree stands with sufficient and insufficient evapotranspiration capacity for maintaining drainage conditions without DNM (Sarkkola et al. 2010, 2013), it is evident that the conventional seed-tree and shelter-wood systems cannot be qualified as CCF. After harvesting the last shelter-trees or seed-trees, these systems result in seedling stands with plausibly far too low evapotranspiration capacity to have any effect on site drainage conditions.

2. Key management factors in peatland forests

2.1. Sustaining drainage conditions

Drainage conditions play a key role in forestry on peatlands, as the lowered GWT increases the aeration of the root zone and creates more favorable conditions for tree growth. In an EM forest, where stand volume and consequently its evapotranspiration capacity are low during the initial stages of stand development, the need for DNMs is evident. The study by Sarkkola et al. (2010) indicated, however, that the condition of ditches had only a marginal effect on the GWT depth in mature stands where the standing volumes were greater than about 120 m^3 ha^{-1} in southern Finland and 150 m^3 ha^{-1} in northern Finland. GWT depth correlated more closely with stand volume than with the condition of ditches, indicating that tree evapotranspiration dominates site drainage conditions in such EM stands. Sarkkola et al. (2012) further showed that when the late summer GWT depth, which is the key-factor for optimal tree growth on drained peatlands, was deeper than 35-40 cm already before DNM, tree growth did not respond to DNM (Fig. 1). Together these findings suggest that DNM may be unnecessary in mature, well-growing EM stands, if tree stand evapotranspiration is dominating water balance during growing season and is able to keep GWT at a level that does not impair tree growth.

A counterargument has been presented that DNM should be done even where it does not markedly lower GWT or improve tree growth (Ahti and Päivänen 1997). In this context, DNM would be necessary as a precautionary measure to keep GWT low during abnormally rainy summers in order to decrease the risk of biotic diseases, such as pine sprout cancer. The study by Sarkkola et al. (2010) indicated, however, that GWT is high during exceptionally wet summers, irrespective of the condition of ditch networks or the volume of the tree stand (its evapotranspiration demand). The options to control GWT during such wet summers are therefore very limited. It is further noteworthy that lowering GWT by DNM becomes increasingly difficult in the future as increased peat decomposition over time elapsed from initial drainage decreases its hydraulic conductivity (Nieminen et al. 2017a).

The relationship between stand characteristics and GWT depth has not been studied in CCF forests. Tree stand transpiration there may be lower than in EM forests with equal stand volume, at least temporarily after harvest. For example, selective CCF harvest of individual large trees leaves behind smaller suppressed trees adapted to shaded conditions, plausibly requiring a recovery period of variable length to retain their full transpiration capacity. Given that CCF forests will have more heterogeneous stand structure than EM forests, the proportion of deciduous trees may be larger than in EM forests with equal stand volume. The varying species composition and associated differences in water-use traits can potentially have significant role in growing season transpiration. Thus, evapotranspiration could also be higher in CCF forests than EM forests with equal stand volume, but this needs to be verified.

Because of smaller variation in stand volumes, it is evident, however, that growing season evapotranspiration in CCF forests in the long term would vary less than in EM forests (Fig. 2). This would support more constant GWT depths than in EM forests, where GWT depths during growing season vary substantially from 10-20 cm below soil surface after clear-cut to about 1 m in mature stands during dry summers with high evapotranspiration (Huttunen et al. 2003). Thus, many biogeochemical processes that may enhance nutrient losses and carbon emissions in EM forests because of high or low GWTs could plausibly be suppressed in CCF forests. For example, redox reactions that enhance phosphorus and carbon exports to water courses in clear-cut EM forests with high GWTs (Kaila et al. 2014, Nieminen et al. 2017b), could play a significantly smaller role in discharge water quality in CCF forests. Similarly, oxidation and mineralization of deep peat layers that may significantly enhance carbon and nutrient release from mature EM forests could have minor role in CCF forests.

2.2. Natural regeneration

Seedling establishment and height development of naturally regenerated Norway spruce (*Picea abies*) seedlings in CCF forests on drained peatlands were studied by Hökkä et al. (2011, 2012), Hökkä and Mäkelä (2014) and Hökkä and Repola (2018). The studies showed that there was significant spruce advance growth in mature stands that could be retained in the gaps (Hökkä et al. 2011), and that during three to five years after gap cutting (gap area 78-490 m^2) several thousands (ha^{-1}) of new spruce seedlings had emerged (Hökkä et al. 2012). Thus, a dense seedling stand was formed in the canopy gaps by the advance growth and the new seedlings that emerged after cutting. Ten years after cutting the average density of the crop seedlings higher than 0.2 m was 2200 ha^{-1} with an average height of about 0.8 m (Hökkä and Repola 2018). The seedlings were almost exclusively Norway spruces. The results from gap cutting are in line with the results of some older Finnish studies reporting abundant advance growth in drained Norway spruce stands on peatland (e.g. Lukkala 1946) and those obtained in Sweden by Hånell (1993), Holgen and Hånell (2000), and Örlander and Karlson (2000) from partially cut spruce stands (shelter-wood cutting). The height growth of the naturally established seedlings in the gaps was slower than after planting on peatland (Hökkä and Mäkelä 2014) but faster than in uneven-aged stands in upland forests (Eerikäinen et al. 2014). The studies thus suggest that partial harvesting in drained spruce dominated peatlands has true potential for successful and sufficient regeneration.

Concerning other commercially valuable species, there is no experimental data on natural regeneration after any kind of CCF cutting on drained peatlands. However, recent results related to the seed-tree method in Scots pine (*Pinus sylvestris*) dominated EM forests indicated high potential for natural regeneration in a relatively short (7 years) time period without any soil preparation (Hökkä et al. 2016a). This potential for natural regeneration is nonetheless dependent on the variation in GWT and vegetation succession in the drained peatland site. As for the spruce seedlings, *Sphagnum* mosses provide a favorable germination substrate for pine seeds, but there is great variation in seedling growth and the occurrence of *Sphagnum* is not always a guarantee for sufficient regeneration (Saarinen 2002). The benefit of *Sphagnum* mosses is rather weak if they have colonized on the raw humus layer, primarily consisting of tree needles, leaves, and forest moss litter (Saarinen 2013). Shallow GWT depth in clear-cut EM forests, while enhancing seedling development on the raw humus layer, may impair germination by favouring the growth and spreading of *Eriophorum vaginatum* vegetation (Saarinen 2013).

GWT is likely to rise less after partial CCF harvests than near-complete seed-tree harvest that typically retains only 15-20 % of the pre-harvest volume. For this reason the results for natural regeneration after seed-tree harvests in EM forests are not directly applicable to CCF forests. Smaller rise in GWT in CCF forests may be adverse regarding the germination of new seedlings, but the growth of established seedlings may be faster than in the seed-tree method. In the absence of any research data from Scots pine dominated CCF forests in terms of regimes that differ markedly form the seed-tree method (e.g., strip or gap harvesting), it is difficult to assess their natural regeneration success. However, as a shade-intolerant species, it is clear that larger harvest openings and lower standing volumes are needed for successful natural regeneration of Scots pine than of shade-tolerant species.

2.3. Tree growth

In the boreal regions, the peatlands drained for forestry were generally forest covered already before drainage, and afforestation of open peatland sites was relatively rare (Paavilainen and Päivänen 1995). Depending on the initial site type and stand characteristics (age, size, tree species, spatial distribution), stand development took different pathways after drainage (Hökkä and Laine 1988, Sarkkola et al. 2005). As a rule, Scots pine dominated the nutrient-poor sites and Norway spruce the more fertile sites in northern Europe, with downy birch (*Betula pubescens* Ehrh) growing as a mixture except for the very nutrient poor Scots pine sites. The age and size structures of the stands were clearly uneven already before drainage (Heikurainen 1971, Gustavsen and Päivänen 1986). This irregularity was still evident or more even pronounced 20–30 years after drainage (Sarkkola et al. 2004, 2005), which was illustrated by the right-skewed stand diameter distributions. However, management of peatland forests with EM involving intermediate thinnings from below and natural competition resulting in high mortality among small-sized trees steered their succession towards more even stand structures (Hökkä and Laine 1988, Sarkkola et al. 2005). Nevertheless, most research results on tree growth in drained peatland forests have been derived from data including different-aged trees and a lot of irregularity in stand structure. This may indirectly indicate that the growth and yield potential of CCF forests on drained peatlands would be at a quite satisfactory level as compared to EM stands.

The growth rates and total yields of drained peatland stands are considered similar as in upland forests, given that high GWT is not limiting tree growth (Hökkä and Penttilä 1999). Because of better nitrogen supply, peatland sites classified as nutrient-poor may have even better growth potential than respective nutrient-poor mineral soil sites. The results from upland forests indicate that the growth of small-sized trees under CCF is significantly impaired by the larger-sized trees that over-compete them for nutrients, light and water (Eerikäinen et al. 2014). However, the development of small-sized trees in peatland forests under CCF could be less affected by the surrounding larger trees. Excess water being the key growth-limiting factor in peatland forests, the water uptake by the large-sized trees may help to maintain satisfactory drainage conditions for small trees. On the other hand, uneven and grouped stand structure was found to decrease stand growth when compared to more even-structured stands on drained peatland (Miina et al. 1991, Miina 1994). Despite of the continued unevenness in drained peatland stand structure long after drainage, there is no data on their long-term response to successful CCF management.

3. Environmental impacts of CCF

3.1. GHG emissions

Land use involving drainage on peatlands generally affects the carbon balance of peat soils negatively, inducing CO_2 losses from the peat into the atmosphere (e.g., IPCC 2014). Forestry is less harmful in this respect than agricultural practices or peat harvesting (Petrescu et al. 2015), foremost because the tree stand and sometimes also the ground vegetation maintain relatively high inputs of new organic matter into the soil (Straková et al. 2010, 2012). These inputs compensate to a varying extent for the CO_2 loss resulting from peat decomposition. Under boreal conditions, Ojanen et al. (2010, 2013) observed that nutrient-rich peat soils generally acted as C sources, whereas moderately nutrient-poor soils, which still sustain forest growth, were close to C neutral or even C sinks. These findings have been supported by other studies as well (e.g., Lohila et al. 2011, Meyer et al. 2013). Furthermore, the C loss from nutrient-rich soils increases with increasing temperature sum (Ojanen et al. 2010, 2013).

In EM forests on drained peatlands, soil CO_2 emissions are highest in mature stands approaching their clear-cutting phase, as their evapotranspiration results in a lower-than-average growing season GWT, thus enabling aerobic decomposition also in deeper peat layers (Ojanen et al. 2010). The average stand volumes maintained in CCF forests would be smaller than in mature EM forests, likely resulting in higher GWT and limited aerobic decomposition in deep peat layers. Supposedly this should decrease soil CO_2 emissions; however, so far there is no data supporting this postulate while no attempts have been made to quantify the potential emissions under CCF. Since the soil C balance depends not only on the rate of decomposition but also on the input rate of new organic matter, both need to be considered when estimating the performance of CCF as an alternative to EM. The input of new organic matter to soil in CCF forests could be more constant over time than in EM forests because the extended time period of low C input after clear-cuts would be avoided. Both ecosystem-scale experiments and modeling studies in upland forests (e.g., Mäkipää et al. 2010, Shanin et al. 2016) have shown, however, that the changes in soil C stocks following harvesting depend on harvest intensity, with intensive harvesting resulting in decreased soil C stock due to decreased litter input to the soil.

Concerning the other major GHGs, CCF could be beneficial in decreasing nitrous oxide (N_2O) emissions by maintaining higher GWT compared to mature EM forests. According to Ojanen et al. (2010), N_2O emissions show a significant positive correlation with GWT depth. N_2O emissions also depend on the soil CN ratio and contribute somewhat notably to the soil GHG balance in nutrient-rich drained sites (Klemedtsson et al. 2005). Emissions of methane (CH_4), in turn, are generally quite low in drained peatlands, where the extent of the oxic surface peat layer allows for efficient oxidation of CH_4. The peat soil between the ditches may even be a small sink of atmospheric CH_4 in sites with mature forests (Ojanen et al. 2010). However, high CH_4 emissions may take place from the ditches (e.g., Minkkinen and Laine 2006). CH_4 emissions depend on GWT depth; emissions increase only after GWT is shallower than -30 cm below the soil surface (Ojanen et al. 2010, 2013). Overall, it seems that CCF could have potential to decrease GHG emissions from peat soils by constantly maintaining GWTs sufficiently deep, but not too deep. Consequently, the soil would still remain as a marginal CH_4 source or sink, but CO_2 and N_2O emissions would be lower than under EM. However, the extent to which this potential could be realized in CCF forests is likely to vary along with cutting intensity and hydrological conditions, which should be addressed in future research.

3.2. Water quality

Drained peatland forests have proven to be a significantly greater source of nutrients, total and dissolved organic carbon (TOC and DOC) as well as suspended sediments (SS) to receiving water courses than undrained peatlands or upland forests (Finér et al. 2010, Nieminen et al. 2015). In countries such as Finland and Sweden, where DNM is undertaken every 20-40 years after the first drainage (Sarkkola et al. 2013), particularly the SS exports remain at a permanently higher level than from undrained sites (Joensuu et al. 1999, Nieminen et al. 2010). In Finland, DNM operations have been estimated to increase SS exports from forest land by over 50% compared to natural background loading, and to cause about two-thirds of the forestry-induced phosphorus (P) exports (Finér et al. 2010). The typical forest regeneration phase in EM with clear-cutting, soil preparation for planting and cleaning of the existing ditch networks increases DOC and N exports especially from the most fertile sites (Lundin 1999, Nieminen 2004, Kaila et al. 2015), and P particularly from nutrient-poor sites (Nieminen 2003, Rodgers et al. 2010, Kaila et al. 2014).

CCF would likely be a significantly smaller source of nutrients and SS than EM with repeated DNMs and clear-cutting. Avoiding DNMs or reducing their need would alone result in a considerable reduction in nutrient and SS exports, as was recently shown in a model-based analysis of alternative EM scenarios (Hökkä et al. 2016b). Furthermore, partial harvesting probably induces lower nutrient release to receiving water courses than clear-cuts, as soil preparation would be unnecessary, and as the remaining trees would uptake at least part of the nutrients released from the relatively smaller amount of logging residues per unit area. Also, the harvest-induced rise of GWT would be smaller due to the evapotranspiration of the remaining tree stand (Pothier et al. 2003), thus plausibly resulting in lower mobilization and release of redox-sensitive nutrients and metals. Recent studies have indicated that the change in redox-conditions in surface peat is the key factor controlling the enhanced phosphate (Kaila et al. 2014) and DOC exports (Nieminen et al. 2015) from drained peatland forests after clear-cutting.

4. Economic profitability of CCF and socially optimal forest management

In addition to the reviewed ecological and biogeochemical studies, which indicate that CCF could be a feasible alternative to EM on drained peatlands, economic studies on forestry management must also be assessed from this perspective. Considering drained peatland forests, some economic research related to EM has been conducted (e.g., Ahtikoski et al. 2012, Hökkä et al. 2016b). Based on those studies, optimal stand management on drained peatlands, particularly in the harsh climatic conditions in northern regions, may include relatively few rather than several silvicultural activities, such as thinning and DNM.

No studies have addressed the economic performance of CCF on drained peatlands. However, studies in upland forests have shown that CCF can in certain cases be a more optimal choice than EM (Pukkala et al. 2011, Tahvonen 2011, 2015, 2016, Ollikainen 2016, Rämö 2017, Jacobsen et al. 2018). Furthermore, Pukkala (2016) and Peura et al. (2018) showed that CCF in upland forests may be a better alternative to EM to provide many ecosystem services. We expect CCF to be an even more attractive alternative in drained peatland forests, because there EM requires more investments than in upland forests. Such investments could be reduced or avoided under CCF (Fig. 2). Overall, even if the growth of trees in CCF forests turned out to be lower than in EM forests producing lower harvest revenues, this could be compensated by fewer investments to regeneration and DNM, and CCF could still be more profitable than EM.

To find the socially optimal forest management alternative, also the environmental benefits and costs to society need to be monetized. On drained peatlands, CCF would plausibly reduce the negative externalities of management (GHG emissions and SS, C, and nutrient export to water courses) compared to EM. Thus, the higher the negative externalities are in these analyses, the more attractive management CCF becomes as an alternative to EM. Previous economic studies assessing EM both on drained peatlands and in upland forests showed that accounting for increased nutrient and SS load and water protection costs had a considerable influence on the socially optimal forest management solution (Miettinen et al. 2012, 2014, 2018). Miettinen et al. (2018) showed that it may be socially non-optimal to conduct DNM in areas with pollution-sensitive headwaters due to the nutrient and SS load damages caused by DNM.

Earlier economic studies on EM in upland forests considering the externalities caused by GHG emissions are provided by, e.g., van Kooten (1995), Niinimäki et al. (2013) and Pihlainen et al. (2014). The studies by Pukkala et al. (2011), Assmuth et al. (2017) and Assmuth and Tahvonen (2018) compared CCF and EM in terms of timber production and carbon sequestration benefits. They concluded that accounting for carbon sequestration benefits will increase the performance of CCF relative to EM. Economic studies including timber production and carbon sequestration would be more complicated on drained peatlands, where carbon loss due to peat decomposition is a key factor when considering the optimal choice of management.

5. Conclusions

Thus far, EM with regular DNMs and clear-cutting in the end of rotation followed by soil preparation and planting or seeding has been the prevailing management principle in drained boreal peatland forests. By reviewing the literature related to economic and environmental performance of forestry on drained peatlands, we aimed to raise the question whether CCF could have potential as an alternative management option to EM.

The reviewed literature suggested that CCF could be an economically and environmentally feasible management option on drained peatlands. Its great advantage is that it may continuously maintain a tree stand with sufficient evapotranspiration capacity to decrease the need for DNM, which introduces high costs and enhances sediment and nutrient exports to receiving water courses. Managing CCF forests in such a way that the ground water levels are lower than in clear-cut EM forests but higher than in mature EM forests could also decrease the greenhouse gas emissions and the negative water quality impacts caused both by anoxic redox reactions and oxidation and mineralization of deep peat layers. Furthermore, the regeneration studies carried out in peatland forests indicated potential for satisfactory natural regeneration in CCF forests. In assessing the economic performance of CCF, the lack of studies on the long-term tree growth response forms an obvious research gap. As there are no studies directly addressing the environmental or economic aspects of CCF *versus* EM in drained peatland forests, the feasibility of CCF is yet to be examined. However, the economic profitability of EM with major investments needed to establish the tree stand and sustain its growth tends to remain relatively low especially at the low productivity peatland sites. At the same time, as indicated by our literature review, there may be high environmental benefits gained by managing peatlands with CCF rather than EM.

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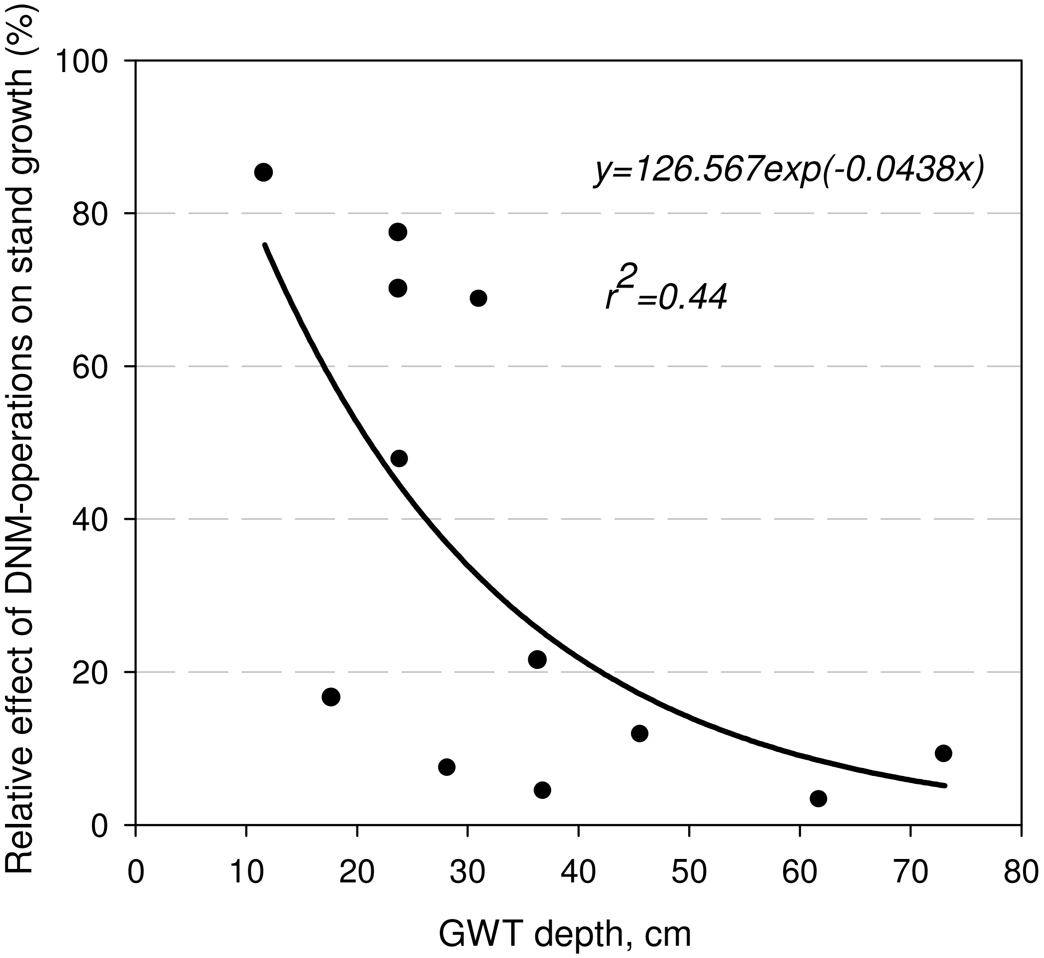
Highlights

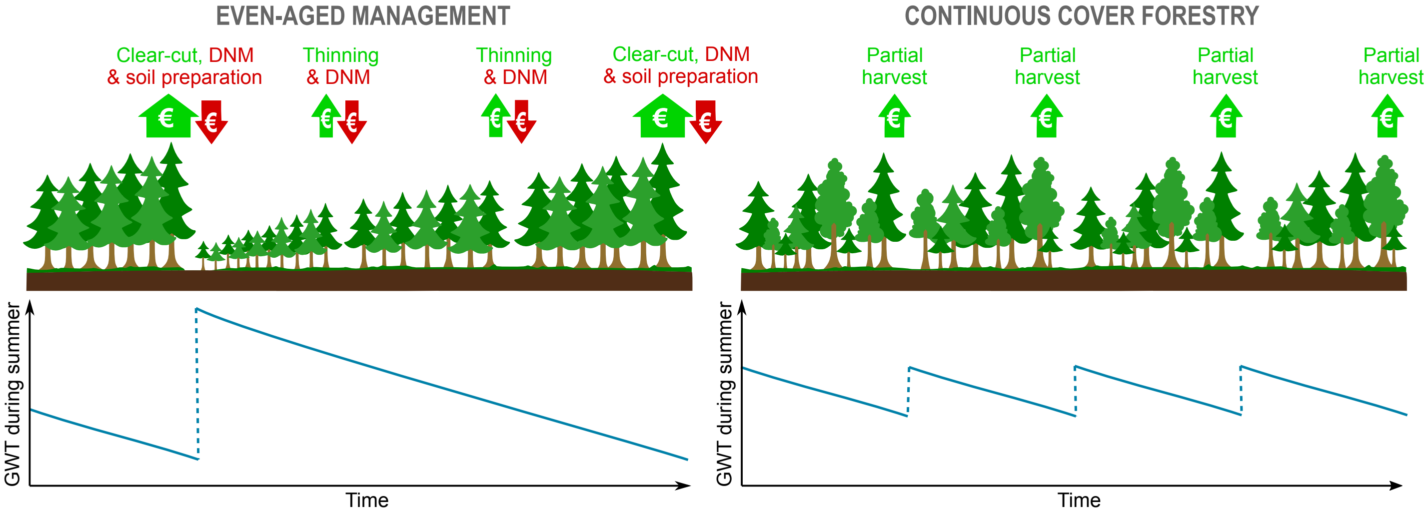
Potential for continuous cover forestry (CCF) on drained peatlands was reviewed

CCF could be a socio-economically feasible alternative to even-aged forestry

Future research should focus on studying CCF on drained peatlands



y=126.567exp(-0.0438x)
r2=0.44
Relative effect of DNM-operations on stand growth (%)
GWT depth, cm
0
20
40
60
80
100
0
10
20
30
40
50
60
70
80


EVEN-AGED MANAGEMENT
Clear-cut, DNM & soil preparation
€
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Thinning & DNM
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Thinning & DNM
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Clear-cut, DNM & soil preparation
€
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GWT during summer
Time
CONTINUOUS COVER FORESTRY
Partial harvest
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Partial harvest
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Partial harvest
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Partial harvest
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GWT during summer
Time

Figure captions

Fig. 1. Relationship between mean annual volume growth increment caused by DNM (% of pre-DNM growth) during 20 years since treatment and the pre-treatment mean late summer (August) GWT depth. Redrawn from Sarkkola et al. (2012).

Fig. 2. Schematic presentation of tree stand development and growing season GWT depth in EM and CCF forests in drained peat soils in Scandinavian conditions, where thinning from below and DNM are standard management practices in EM forests. The arrows pointing downwards illustrate harvest revenues and those pointing upwards are the costs incurred by forest management operations.