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3

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15

16 **Abstract**

17

18 Environmental and economic performance of forestry on drained peatlands was reviewed to consider
19 whether continuous cover forestry (CCF) could be a feasible alternative to even-aged management (EM).
20 CCF was regarded feasible particularly because continuously maintaining a tree stand with significant
21 transpiration and interception capacity would decrease the need for ditch network maintenance. Managing
22 CCF forests in such a way that the ground water levels are lower than in clear-cut EM forests but higher than
23 in mature EM forests could decrease greenhouse gas emissions and negative water quality impacts caused
24 both by anoxic redox reactions and oxidation and mineralization of deep peat layers. Regeneration studies
25 indicated potential for satisfactory natural regeneration under CCF on drained peatlands. An economic
26 advantage in CCF over EM is that fewer investments are needed to establish the forest stand and sustain its
27 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

56 maintenance (DNM) operations are recommended every 20-40 years to sustain and improve drainage
57 conditions (Sikström and Hökkä 2016). After clear-cutting, some type of soil preparation in conjunction with
58 DNM, e.g., ditch-mounding, is considered necessary to establish a new tree stand and lower the ground
59 water table (GWT) that is temporarily raised by harvesting the tree stand with significant evapotranspiration
60 capacity (Heikurainen and Päivänen 1970, Päivänen 1982, Lundin 2000).

61

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

71

72 An environmental problem in EM on drained peatlands is also that carbon dioxide (CO₂) emissions from soil
73 may be so high that the drained sites become net sources of CO₂ to the atmosphere, unlike in pristine
74 peatlands and upland forests. This may be the case particularly in the most nitrogen rich sites, and in highly-
75 stocked stands with mature trees, as their transpiration demand results in a low GWT and aerobic
76 decomposition in deep peat layers (Ojanen et al. 2010, 2013).

77

78 Since EM has detrimental impacts on several ecosystem services provided by peatlands, and is less
79 profitable on peatlands (Kojola et al. 2012) than in uplands (e.g., Hynynen et al. 2015), the demand for
80 alternative management options, such as continuous cover forestry (CCF), has increased. CCF can have
81 potential on drained peatlands because continuously maintaining a tree stand with significant transpiration
82 and interception capacity could decrease the need for DNM (Sarkkola et al. 2010, 2013). Furthermore, natural
83 regeneration, a crucial factor for successful implementation of CCF, could be a feasible option particularly

84 on peatlands, where ample soil moisture and the occurrence of *Sphagnum* favor seedling germination (Place
85 1955, Heinselman 1957, Wood and Jeglum 1984) and establishment. Several studies conducted in the
86 Nordic countries have shown successful natural regeneration in spruce mire sites after partial cutting
87 (Lukkala 1946, Hånell 1993, Holgen and Hånell 2000, Örlander and Karlson 2000)

88

89 Except for the studies researching natural regeneration success in small canopy gaps (Hökkä et al. 2011,
90 2012, Hökkä and Mäkelä 2014), no attempts have been made to study the feasibility of specifically CCF on
91 drained boreal peatlands. By conducting a literature review our aim was to raise the question whether CCF
92 has potential as an economically, environmentally, and socially feasible management option on drained
93 peatlands.

94

95 The applied definition for CCF in our review is relatively broad, i.e., all management options which do not
96 aim for an even-aged stand structure, are based on natural regeneration, and retain a significant proportion of
97 the tree stand after harvesting, are considered as CCF. Thus, executing clear-cuts in small patches or narrow
98 strips of trees is considered CCF as long as the purpose is to keep most of the area continuously canopy-
99 covered and artificial regeneration is not applied. Retaining significant proportion of the tree stand after
100 harvesting is particularly important as we hypothesize that such management can significantly decrease the
101 need for DNM. Although strict limits cannot be given to distinguish the tree stands with sufficient and
102 insufficient evapotranspiration capacity for maintaining drainage conditions without DNM (Sarkkola et al.
103 2010, 2013), it is evident that the conventional seed-tree and shelter-wood systems cannot be qualified as
104 CCF. After harvesting the last shelter-trees or seed-trees, these systems result in seedling stands with
105 plausibly far too low evapotranspiration capacity to have any effect on site drainage conditions.

106

107 2. Key management factors in peatland forests

108

109 2.1. Sustaining drainage conditions

110

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

124
125 A counterargument has been presented that DNM should be done even where it does not markedly lower
126 GWT or improve tree growth (Ahti and Päivänen 1997). In this context, DNM would be necessary as a
127 precautionary measure to keep GWT low during abnormally rainy summers in order to decrease the risk of
128 biotic diseases, such as pine sprout cancer. The study by Sarkkola et al. (2010) indicated, however, that
129 GWT is high during exceptionally wet summers, irrespective of the condition of ditch networks or the
130 volume of the tree stand (its evapotranspiration demand). The options to control GWT during such wet
131 summers are therefore very limited. It is further noteworthy that lowering GWT by DNM becomes
132 increasingly difficult in the future as increased peat decomposition over time elapsed from initial drainage
133 decreases its hydraulic conductivity (Nieminen et al. 2017a).

134
135 The relationship between stand characteristics and GWT depth has not been studied in CCF forests. Tree
136 stand transpiration there may be lower than in EM forests with equal stand volume, at least temporarily after
137 harvest. For example, selective CCF harvest of individual large trees leaves behind smaller suppressed trees

138 adapted to shaded conditions, plausibly requiring a recovery period of variable length to retain their full
139 transpiration capacity. Given that CCF forests will have more heterogeneous stand structure than EM forests,
140 the proportion of deciduous trees may be larger than in EM forests with equal stand volume. The varying
141 species composition and associated differences in water-use traits can potentially have significant role in
142 growing season transpiration. Thus, evapotranspiration could also be higher in CCF forests than EM forests
143 with equal stand volume, but this needs to be verified.

144
145 Because of smaller variation in stand volumes, it is evident, however, that growing season
146 evapotranspiration in CCF forests in the long term would vary less than in EM forests (Fig. 2). This would
147 support more constant GWT depths than in EM forests, where GWT depths during growing season vary
148 substantially from 10-20 cm below soil surface after clear-cut to about 1 m in mature stands during dry
149 summers with high evapotranspiration (Huttunen et al. 2003). Thus, many biogeochemical processes that
150 may enhance nutrient losses and carbon emissions in EM forests because of high or low GWTs could
151 plausibly be suppressed in CCF forests. For example, redox reactions that enhance phosphorus and carbon
152 exports to water courses in clear-cut EM forests with high GWTs (Kaila et al. 2014, Nieminen et al. 2017b),
153 could play a significantly smaller role in discharge water quality in CCF forests. Similarly, oxidation and
154 mineralization of deep peat layers that may significantly enhance carbon and nutrient release from mature
155 EM forests could have minor role in CCF forests.

156 157 2.2. Natural regeneration

158

159 Seedling establishment and height development of naturally regenerated Norway spruce (*Picea abies*)
160 seedlings in CCF forests on drained peatlands were studied by Hökkä et al. (2011, 2012), Hökkä and Mäkelä
161 (2014) and Hökkä and Repola (2018). The studies showed that there was significant spruce advance growth
162 in mature stands that could be retained in the gaps (Hökkä et al. 2011), and that during three to five years
163 after gap cutting (gap area 78-490 m²) several thousands (ha⁻¹) of new spruce seedlings had emerged (Hökkä
164 et al. 2012). Thus, a dense seedling stand was formed in the canopy gaps by the advance growth and the new

165 seedlings that emerged after cutting. Ten years after cutting the average density of the crop seedlings higher
166 than 0.2 m was 2200 ha⁻¹ with an average height of about 0.8 m (Hökkä and Repola 2018). The seedlings
167 were almost exclusively Norway spruces. The results from gap cutting are in line with the results of some
168 older Finnish studies reporting abundant advance growth in drained Norway spruce stands on peatland (e.g.
169 Lukkala 1946) and those obtained in Sweden by Hånell (1993), Holgen and Hånell (2000), and Örlander and
170 Karlson (2000) from partially cut spruce stands (shelter-wood cutting). The height growth of the naturally
171 established seedlings in the gaps was slower than after planting on peatland (Hökkä and Mäkelä 2014) but
172 faster than in uneven-aged stands in upland forests (Eerikäinen et al. 2014). The studies thus suggest that
173 partial harvesting in drained spruce dominated peatlands has true potential for successful and sufficient
174 regeneration.

175
176 Concerning other commercially valuable species, there is no experimental data on natural regeneration after
177 any kind of CCF cutting on drained peatlands. However, recent results related to the seed-tree method in
178 Scots pine (*Pinus sylvestris*) dominated EM forests indicated high potential for natural regeneration in a
179 relatively short (7 years) time period without any soil preparation (Hökkä et al. 2016a). This potential for
180 natural regeneration is nonetheless dependent on the variation in GWT and vegetation succession in the
181 drained peatland site. As for the spruce seedlings, *Sphagnum* mosses provide a favorable germination
182 substrate for pine seeds, but there is great variation in seedling growth and the occurrence of *Sphagnum* is
183 not always a guarantee for sufficient regeneration (Saarinen 2002). The benefit of *Sphagnum* mosses is
184 rather weak if they have colonized on the raw humus layer, primarily consisting of tree needles, leaves, and
185 forest moss litter (Saarinen 2013). Shallow GWT depth in clear-cut EM forests, while enhancing seedling
186 development on the raw humus layer, may impair germination by favouring the growth and spreading of
187 *Eriophorum vaginatum* vegetation (Saarinen 2013).

188
189 GWT is likely to rise less after partial CCF harvests than near-complete seed-tree harvest that typically
190 retains only 15-20 % of the pre-harvest volume. For this reason the results for natural regeneration after
191 seed-tree harvests in EM forests are not directly applicable to CCF forests. Smaller rise in GWT in CCF
192 forests may be adverse regarding the germination of new seedlings, but the growth of established seedlings

193 may be faster than in the seed-tree method. In the absence of any research data from Scots pine dominated
194 CCF forests in terms of regimes that differ markedly from the seed-tree method (e.g., strip or gap
195 harvesting), it is difficult to assess their natural regeneration success. However, as a shade-intolerant species,
196 it is clear that larger harvest openings and lower standing volumes are needed for successful natural
197 regeneration of Scots pine than of shade-tolerant species.

199 2.3. Tree growth

201 In the boreal regions, the peatlands drained for forestry were generally forest covered already before
202 drainage, and afforestation of open peatland sites was relatively rare (Paavilainen and Päivänen 1995).
203 Depending on the initial site type and stand characteristics (age, size, tree species, spatial distribution), stand
204 development took different pathways after drainage (Hökkä and Laine 1988, Sarkkola et al. 2005). As a rule,
205 Scots pine dominated the nutrient-poor sites and Norway spruce the more fertile sites in northern Europe,
206 with downy birch (*Betula pubescens* Ehrh) growing as a mixture except for the very nutrient poor Scots pine
207 sites. The age and size structures of the stands were clearly uneven already before drainage (Heikurainen
208 1971, Gustavsen and Päivänen 1986). This irregularity was still evident or more even pronounced 20–30
209 years after drainage (Sarkkola et al. 2004, 2005), which was illustrated by the right-skewed stand diameter
210 distributions. However, management of peatland forests with EM involving intermediate thinnings from
211 below and natural competition resulting in high mortality among small-sized trees steered their succession
212 towards more even stand structures (Hökkä and Laine 1988, Sarkkola et al. 2005). Nevertheless, most
213 research results on tree growth in drained peatland forests have been derived from data including different-
214 aged trees and a lot of irregularity in stand structure. This may indirectly indicate that the growth and yield
215 potential of CCF forests on drained peatlands would be at a quite satisfactory level as compared to EM
216 stands.

217
218 The growth rates and total yields of drained peatland stands are considered similar as in upland forests, given
219 that high GWT is not limiting tree growth (Hökkä and Penttilä 1999). Because of better nitrogen supply,
220 peatland sites classified as nutrient-poor may have even better growth potential than respective nutrient-poor

221 mineral soil sites. The results from upland forests indicate that the growth of small-sized trees under CCF is
222 significantly impaired by the larger-sized trees that over-compete them for nutrients, light and water
223 (Eerikäinen et al. 2014). However, the development of small-sized trees in peatland forests under CCF could
224 be less affected by the surrounding larger trees. Excess water being the key growth-limiting factor in
225 peatland forests, the water uptake by the large-sized trees may help to maintain satisfactory drainage
226 conditions for small trees. On the other hand, uneven and grouped stand structure was found to decrease
227 stand growth when compared to more even-structured stands on drained peatland (Miina et al. 1991, Miina
228 1994). Despite of the continued unevenness in drained peatland stand structure long after drainage, there is
229 no data on their long-term response to successful CCF management.

231 3. Environmental impacts of CCF

233 3.1. GHG emissions

235 Land use involving drainage on peatlands generally affects the carbon balance of peat soils negatively,
236 inducing CO₂ losses from the peat into the atmosphere (e.g., IPCC 2014). Forestry is less harmful in this
237 respect than agricultural practices or peat harvesting (Petrescu et al. 2015), foremost because the tree stand
238 and sometimes also the ground vegetation maintain relatively high inputs of new organic matter into the soil
239 (Straková et al. 2010, 2012). These inputs compensate to a varying extent for the CO₂ loss resulting from
240 peat decomposition. Under boreal conditions, Ojanen et al. (2010, 2013) observed that nutrient-rich peat
241 soils generally acted as C sources, whereas moderately nutrient-poor soils, which still sustain forest growth,
242 were close to C neutral or even C sinks. These findings have been supported by other studies as well (e.g.,
243 Lohila et al. 2011, Meyer et al. 2013). Furthermore, the C loss from nutrient-rich soils increases with
244 increasing temperature sum (Ojanen et al. 2010, 2013).

246 In EM forests on drained peatlands, soil CO₂ emissions are highest in mature stands approaching their clear-
247 cutting phase, as their evapotranspiration results in a lower-than-average growing season GWT, thus
248 enabling aerobic decomposition also in deeper peat layers (Ojanen et al. 2010). The average stand volumes

249 maintained in CCF forests would be smaller than in mature EM forests, likely resulting in higher GWT and
250 limited aerobic decomposition in deep peat layers. Supposedly this should decrease soil CO₂ emissions;
251 however, so far there is no data supporting this postulate while no attempts have been made to quantify the
252 potential emissions under CCF. Since the soil C balance depends not only on the rate of decomposition but
253 also on the input rate of new organic matter, both need to be considered when estimating the performance of
254 CCF as an alternative to EM. The input of new organic matter to soil in CCF forests could be more constant
255 over time than in EM forests because the extended time period of low C input after clear-cuts would be
256 avoided. Both ecosystem-scale experiments and modeling studies in upland forests (e.g., Mäkipää et al.
257 2010, Shanin et al. 2016) have shown, however, that the changes in soil C stocks following harvesting
258 depend on harvest intensity, with intensive harvesting resulting in decreased soil C stock due to decreased
259 litter input to the soil.

260
261 Concerning the other major GHGs, CCF could be beneficial in decreasing nitrous oxide (N₂O) emissions by
262 maintaining higher GWT compared to mature EM forests. According to Ojanen et al. (2010), N₂O emissions
263 show a significant positive correlation with GWT depth. N₂O emissions also depend on the soil CN ratio and
264 contribute somewhat notably to the soil GHG balance in nutrient-rich drained sites (Klemedtsson et al.
265 2005). Emissions of methane (CH₄), in turn, are generally quite low in drained peatlands, where the extent of
266 the oxic surface peat layer allows for efficient oxidation of CH₄. The peat soil between the ditches may even
267 be a small sink of atmospheric CH₄ in sites with mature forests (Ojanen et al. 2010). However, high CH₄
268 emissions may take place from the ditches (e.g., Minkkinen and Laine 2006). CH₄ emissions depend on
269 GWT depth; emissions increase only after GWT is shallower than -30 cm below the soil surface (Ojanen et
270 al. 2010, 2013). Overall, it seems that CCF could have potential to decrease GHG emissions from peat soils
271 by constantly maintaining GWTs sufficiently deep, but not too deep. Consequently, the soil would still
272 remain as a marginal CH₄ source or sink, but CO₂ and N₂O emissions would be lower than under EM.
273 However, the extent to which this potential could be realized in CCF forests is likely to vary along with
274 cutting intensity and hydrological conditions, which should be addressed in future research.

276 3.2. Water quality

277

278 Drained peatland forests have proven to be a significantly greater source of nutrients, total and dissolved
279 organic carbon (TOC and DOC) as well as suspended sediments (SS) to receiving water courses than
280 undrained peatlands or upland forests (Finér et al. 2010, Nieminen et al. 2015). In countries such as Finland
281 and Sweden, where DNM is undertaken every 20-40 years after the first drainage (Sarkkola et al. 2013),
282 particularly the SS exports remain at a permanently higher level than from undrained sites (Joensuu et al.
283 1999, Nieminen et al. 2010). In Finland, DNM operations have been estimated to increase SS exports from
284 forest land by over 50% compared to natural background loading, and to cause about two-thirds of the
285 forestry-induced phosphorus (P) exports (Finér et al. 2010). The typical forest regeneration phase in EM
286 with clear-cutting, soil preparation for planting and cleaning of the existing ditch networks increases DOC
287 and N exports especially from the most fertile sites (Lundin 1999, Nieminen 2004, Kaila et al. 2015), and P
288 particularly from nutrient-poor sites (Nieminen 2003, Rodgers et al. 2010, Kaila et al. 2014).

289

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

301

302 4. Economic profitability of CCF and socially optimal forest management

303

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

310
311 No studies have addressed the economic performance of CCF on drained peatlands. However, studies in
312 upland forests have shown that CCF can in certain cases be a more optimal choice than EM (Pukkala et al.
313 2011, Tahvonen 2011, 2015, 2016, Ollikainen 2016, Rämö 2017, Jacobsen et al. 2018). Furthermore,
314 Pukkala (2016) and Peura et al. (2018) showed that CCF in upland forests may be a better alternative to EM
315 to provide many ecosystem services. We expect CCF to be an even more attractive alternative in drained
316 peatland forests, because there EM requires more investments than in upland forests. Such investments could
317 be reduced or avoided under CCF (Fig. 2). Overall, even if the growth of trees in CCF forests turned out to
318 be lower than in EM forests producing lower harvest revenues, this could be compensated by fewer
319 investments to regeneration and DNM, and CCF could still be more profitable than EM.

320
321 To find the socially optimal forest management alternative, also the environmental benefits and costs to
322 society need to be monetized. On drained peatlands, CCF would plausibly reduce the negative externalities
323 of management (GHG emissions and SS, C, and nutrient export to water courses) compared to EM. Thus,
324 the higher the negative externalities are in these analyses, the more attractive management CCF becomes as
325 an alternative to EM. Previous economic studies assessing EM both on drained peatlands and in upland
326 forests showed that accounting for increased nutrient and SS load and water protection costs had a
327 considerable influence on the socially optimal forest management solution (Miettinen et al. 2012, 2014,
328 2018). Miettinen et al. (2018) showed that it may be socially non-optimal to conduct DNM in areas with
329 pollution-sensitive headwaters due to the nutrient and SS load damages caused by DNM.

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

339 5. Conclusions

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

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

359 sustain its growth tends to remain relatively low especially at the low productivity peatland sites. At the
360 same time, as indicated by our literature review, there may be high environmental benefits gained by
361 managing peatlands with CCF rather than EM.

362

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364

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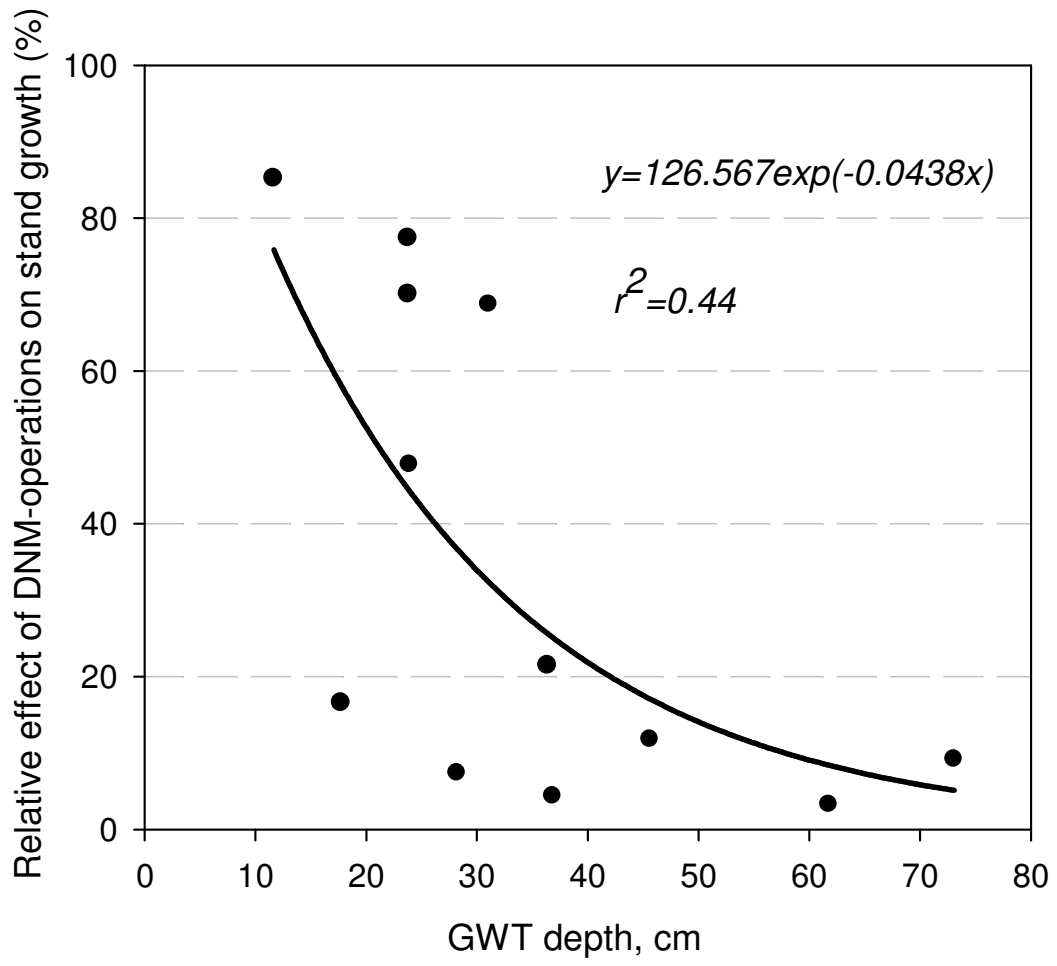
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Highlights

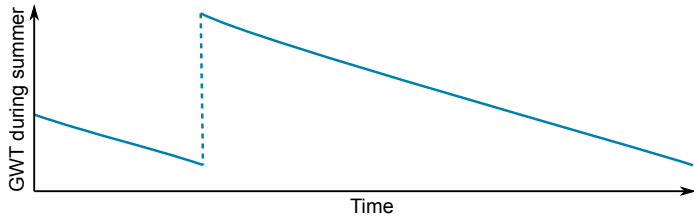
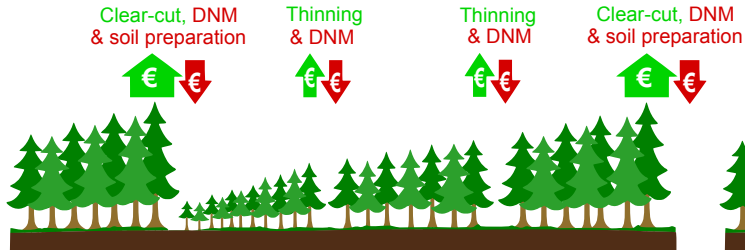
Potential for continuous cover forestry (CCF) on drained peatlands was reviewed

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

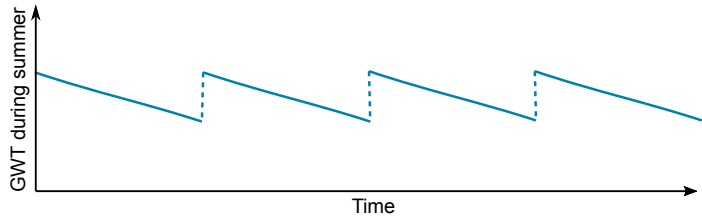
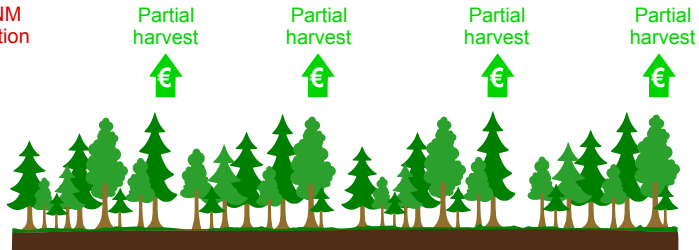
Future research should focus on studying CCF on drained peatlands



EVEN-AGED MANAGEMENT



CONTINUOUS COVER FORESTRY



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4 Figure captions

5

6 Fig. 1. Relationship between mean annual volume growth increment caused by DNM (% of pre-DNM growth) during
7 20 years since treatment and the pre-treatment mean late summer (August) GWT depth. Redrawn from Sarkkola et
8 al. (2012).

9

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

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