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A synthesis of the impacts of ditch network maintenance on the quantity and quality of runoff from drained boreal peatland forests

Mika Nieminen, Marjo Palviainen, Sakari Sarkkola, Ari Laurén, Hannu Marttila, Leena Finér

Mika Nieminen: Natural Resources Institute Finland, Helsinki, Viikinkaari 4, FI-00790 Helsinki, Finland. e-mail: mika.nieminen@luke.fi. Tel.: +358-29-532-2399

Marjo Palviainen: Department of Forest Sciences, University of Helsinki, P.O. Box 27, 00014 Helsinki, Finland. e-mail: marjo.palviainen@helsinki.fi

Sakari Sarkkola: Natural Resources Institute Finland, Helsinki, Viikinkaari 4, FI-00790 Helsinki, Finland. e-mail: sakari.sarkkola@luke.fi

Ari Laurén: Natural Resources Institute Finland, Joensuu, P.O. Box 68, FI-80101 Joensuu, Finland. e-mail: ari.lauren@luke.fi

Hannu Marttila: Water Resources and Environmental Engineering Research Group, P.O. Box 4300, FI-90014 University of Oulu. e-mail: hannu.marttila@oulu.fi

Leena Finér: Natural Resources Institute Finland, Joensuu, P.O. Box 68, FI-80101 Joensuu, Finland. e-mail: leena.finer@luke.fi

Word count: 6214

This is a post-peer-review, pre-copyedit version of an article published in Ambio.

The final authenticated version is available online at: https://doi.org/10.1007/s13280-017-0966-y.

A synthesis of the impacts of ditch network maintenance on the quantity and quality of runoff from drained boreal peatland forests

Abstract

Drained peatlands are an important source of forest biomass in boreal regions and ditch network maintenance (DNM) operations may be needed to restore the drainage functions of ditches. By reviewing the available literature, as well as utilizing an existing hydrological model and analysing the characteristics of eroded sediments, we assessed the impacts of DNM on runoff and exports of suspended solids (SS), dissolved organic carbon (DOC), nitrogen (N), and phosphorus (P). In general, DNM had minor impact on runoff and dissolved N and P, and it decreased rather than increased DOC exports. To increase the understanding of the hydrochemical impacts of DNM, future research should focus on the characteristics of SS and particulate nutrient exports. A major gap in knowledge is also the very limited regional representativeness of the available studies. High erosion risk in the ditches reaching the mineral soil below peat should be acknowledged when planning mitigation measures.

Key words: DOC, nitrogen, phosphorus, runoff, suspended solids, water quality

1. Introduction

Due to the recent efforts to shift to more bio-based economy, the demand for forest biomass is increasing. In the Nordic countries, a significant proportion of this demand is covered by the biomass harvest from the peatlands drained for forestry. About 15 million ha of peatlands and paludified mineral soils have been drained for forestry purposes in the temperate and boreal regions and 10 million ha of them in the Baltic Sea Region countries (Paavilainen and Päivänen 1995). There is no longer almost any first-time drainage of pristine peatlands carried out to increase tree production. However, ditch network maintenance (DNM) is often used to restore the drainage functions of the ditches in order to improve and maintain the stand growth achieved by the first-time drainage (Sikström and Hökkä 2016). DNM can be done by clearing the old ditches (ditch cleaning) to their original depth (80-100 cm) or digging new ditches between the old ones (supplementary ditching), or as a combination of both. In Finland, forest management guidelines recommend 1-2 DNM operations during the stand rotation (Good forest management…2007) and between 52 000 and 83 000 ha year^{-1} of drained peatlands were treated with DNM during 1990-2010 (Päivänen and Hånell 2012). Lately, DNM has received increasing attention also in Sweden (Bergquist et al. 2016). Along with the demand to replace fossil fuels with renewable ones, forestry measures to maintain and increase tree growth are needed, and not only in forests on mineral soils, but also on drained peatland forests. DNM has been shown to increase tree growth in Scots pine (*Pinus sylvestris* L.) stands by up to about 40 m^3 ha^{-1} during 20 years, when nutrients are not limiting tree growth (Sikström and Hökkä 2016).

Despite that DNM may be needed to sustain tree growth, a serious concern has been attributed to its impacts on the exports of suspended solids (SS), nutrients and heavy metals to receiving water bodies. While most studies indicate that DNM has minor impacts on runoff compared with initial, first-time drainage (Joensuu et al. 1999; Åström et al. 2001b; Koivusalo et al. 2008), particularly the increase in SS export can be large (Joensuu et al. 1999; Marttila and Kløve 2010a; Nieminen et al. 2010). In Finland, DNM is currently regarded as the most harmful forestry practice for the surface water quality (Joensuu et al. 2002; Finér et al. 2010). Finér et al. (2010) estimated that DNM increases SS export from forest land in Finland by over 50% compared to natural background loading, and causes about two-thirds of the forestry-induced phosphorus exports. For mitigating the detrimental impacts of DNM on water quality, more scientific knowledge is needed in all countries with large areas of drained peatlands. A problem is that most of the scientific studies are from

Finland, and many of them are published only in Finnish. Their accessibility could be increased by presenting a synthesis of the results to a wider audience in English.

In this paper we review and synthesize the results of the studies on the effects of DNM on runoff and the exports of suspended solids (SS), dissolved organic carbon (DOC), as well as the different species of N and P, including Finnish language publications. By also utilizing an existing hydrological model and analysing the characteristics of eroded sediments , we aimed to increase the understanding of the mechanisms behind the variation in runoff and element exports after DNM. Better understanding of the mechanisms controlling runoff quantity and quality from DNM areas would be of great importance for a number of purposes, such as modeling the short and long term hydrochemical effects of DNM, as well as assessing cost-efficient means to mitigate harmful impacts on water quality under differing site and climatic conditions.

2 Material and methods

2.1. Literature review

Our principal selection criteria in reviewing relevant literature was to include peer reviewed papers, but particularly for the long-term changes (>10 years) in SS and DOC exports, technical reports were the only available source (Joensuu et al. 2006; Joensuu 2013). In addition to using different search engines (e.g., Google Scholar), we contacted the researchers with published papers on the impacts of DNM. We found a total of 23 studies, which reported hydrological and hydrochemical impacts of DNM (Table 1). One of them was from Sweden, the remaining 22 from Finland. Three of them were modeling studies. Our initial aim was to also include heavy metals in this review, but the available literature was too scarce to synthesize about the impacts of DNM, particularly as regards the biogeochemically active species of heavy metals.

Our review included both thick-peated (>1-2 m) and shallow-peated soils, where the ditches after DNM reached the mineral soil below peat, but not paludified mineral soils with no peat above mineral subsoil. The tree stands were dominated by Scots pine (*Pinus sylvestris* L.) or Norway spruce (*Picea abies* Karst.). In many catchments, downy birch (*Betula pubescent*) was also frequent. The DNMs were done in the first rotation stands after initial drainage at the mid-rotation stage, where the stand stem volume varies generally between 20-30 m^3 ha^{-1} in the very nutrient poor sites and 100-150 m^3 ha^{-1} in the fertile sites. The DNMs involved only ditch cleaning or combination of both ditch cleaning and supplementary ditching.

2.2. Hydrological modelling

Because of the large number of the factors contributing to runoff after DNM, comparison between different studies is complicated and challenging. The factors contributing to the variation in drainage-induced runoff include hydrological characteristics of peat and ditch network, climatic conditions and weather conditions during the study period, vegetation evapotranspiration and its response to DNM, proportion of the DNM area of the whole catchment area, and the length of the monitoring period after DNM (Koivusalo et al. 2008). Owing to the large number of the contributing factors and their dynamic interactions, empirical studies are not particularly powerful in increasing the understanding of the impacts of DNM on runoff. Therefore, we complemented our literature review of past empirical studies by using the FEMMA (model for Forestry Environmental Management) hydrological process model (Koivusalo et al. 2008) to illustrate the impacts of soil and ditch network characteristics, vegetation evapotranspiration, and climatic conditions on runoff in DNM-treated peatlands.

The FEMMA-model consists of sub-models for snow accumulation and melt, interception and transpiration in the overstory and understory vegetation layers, and soil- and ground water interactions, and runoff generation (Koivusalo et al. 2008). Soil hydrology is described in two dimensions as a cross-section between open ditch drains. The model allows parameterization of soil hydrological properties, i.e. water retention characteristics and hydraulic conductivity, in vertically distributed layers located side by side each other in the strip between the ditches. The soil profile is composed of layers located one upon another, and extends from the soil surface to the impermeable bottom. Canopy and snow sub-models are driven by daily standard meteorological input data (air temperature, precipitation, relative humidity, wind speed, and downward short and long-wave radiation) and soil water movement and runoff generation processes are then simulated using potential transpiration and throughfall/snowmelt series available from the canopy and snow sub-models (Koivusalo et al. 2008).

The FEMMA model was applied to produce scenarios for the impacts of DNM on annual runoffs by increasing the ditch depth from 25 cm before DNM to 100 cm after it and by using different parameters for peat hydraulic properties, weather conditions, and the volume of the tree stand (its transpiration demand). The ditch spacing in the simulations was 40 meters, following the current guidelines for DNM in Finland (Good forest management…2007), and the ditch depth 25 cm was set to illustrate a pre-DNM ditch network with poor drainage capacity due to vegetation colonisation and other processes decreasing ditch depth (Marttila and Kløve 2010a), and the depth of 100 cm illustrated a recently cleaned ditch network. The daily time series of air temperature, precipitation, relative humidity, wind speed, and downward short and long-wave radiation for Tuusula in southern Finland (60°27' N; 24°57' E) and Muhos in northern (64°43' N; 26°0' E) Finland during 2009 (a meteorologically typical year in those areas) were selected as the meteorological input data. The peat was either slightly decomposed Sphagnum peat with high hydraulic conductivity (2.12 cm h^{-1}) or highly humified Carex peat with low hydraulic conductivity (0.58 cm h^{-1}). The parameters of the water retention curves of these peats were obtained from the work by Päivänen (1973).The tree species was Scots pine (*Pinus sylvestris* L.) and the tree stand stem volume in the simulations varied from 50 to 250 m^3 ha^{-1}.

2.3. C, N, and P in eroded sediments

In addition to reviewing the literature and modelling runoff for increasing the understanding of the impacts of DNM on water quantity and quality, we analysed data of a small-scale empirical study (Table 2). For assessing the variation in particulate nitrogen (N) and phosphorus (P) exported from DNM areas along with eroded sediments, we analysed the N and P contents of the deposited sediments sampled from the ponds of 12 catchment areas. The catchment areas of the ponds varied between 21 and 172 ha. The sediment samples were collected from the surface 0-10 cm sediment layer from each of the 12 ponds. One sample was pure peat and four samples pure or almost pure mineral soil, while the remaining seven samples were different mixtures of peat and mineral soil. The mineral soil in the samples was classified according to its texture into coarse-textured (grain size > 0.63 mm), medium-textured (grain size 0.063-0.63 mm), and fine-textured (grain size <0.063 mm) soils.

In the laboratory, the samples were analysed for total carbon (C) and N using a LECO CHN-1000 analyser (LECO® Corporation, USA), and for total P using ICP-emission spectrometer (iCAP 6500 Duo, Thermo Fisher Scientific, Waltham, MA, United Kingdom) after dry ashing (550 ^{o}C) and dissolution of the ash in 0.1 M HCl. Pretreatment of the sediment samples involved drying to a constant mass at 60°C and homogenization by milling (sieve mesh diameter 0.2 mm).

3 Impacts of DNM

3.1 Runoff

The theory behind the impact of DNM on water balance suggests that runoff should increase immediately after DNM as the water level in the ditches is lowered and gravitation increases water flow into ditches until a new equilibrium is achieved between the water level in the ditches and that in their watershed (Koivusalo et al. 2008). Another factor that could increase runoff is the degeneration of understory wetland vegetation, and subsequent decrease in its evapotranspiration. However, the available empirical studies generally reported no changes rather than clear increases in annual runoff during the first 1-2 years after DNM (e.g., Joensuu et al. 1999; Åström et al. 2002). Hansen et al. (2013) estimated an increase of up to 10 mm in runoff during the first month after DNM and no differences between treatment and control catchments thereafter.

The runoff scenarios produced by the FEMMA model showed that DNM with 40 m ditch spacing and increasing ditch depth from 25 to 100 cm resulted in a 50-75 mm increase in runoff during the first year after DNM in the *Sphagnum* peat dominated peatland in southern Finland, and 40-70 mm increase in northern Finland (Fig. 1). The increase in runoff in the more decomposed *Carex* peat was 20-30 mm lower than in the *Sphagnum* peat. Given that the average annual runoff in Finland is about 300 mm, DNM increased runoff by 7-25%. This relatively small increase together with the uncertainty involved in the calibration period/control area study approach (Laurén et al. 2009) may explain why the available empirical catchment studies did not report clear changes in annual runoff after DNM (e.g., Joensuu et al. 1999; Åström et al. 2002; Tuukkanen et al. 2016). It should also be noted that, although the simulations showed slightly increased runoff soon after DNM, it likely decreases in the long term, as the increased growth and leaf area of the tree stand increase interception and transpiration. This was seen in our modelling results as a negative relationship between tree stand volume and runoff (Fig. 1). This was also supported by the studies, which indicated that DNM may not increase tree growth in mature stands (Sarkkola et al. 2010; 2012; 2013), as the water uptake of the forest stand may be sufficient to maintain good aeration in the root zone, despite the poor condition of the ditch network.

Despite that DNM may have minor impacts on annual runoff volumes, it may induce significant changes in runoff dynamics. For example, DNM may initially increase peak runoffs thereby increasing the erosive force of water and SS exports (Tuukkanen et al. 2016). Many studies reported increases in low flow rates after initial, first-time draining of peatlands (Ahti 1987; Sirin et al. 1991; Johnson 1998; Prévost et al. 1999), but, to our knowledge, the effect of DNM on low flows has not been studied.

3.2 Exports of suspended solids

The exports of SS from drained peatlands before DNM are on average <10-20 kg ha^{-1} year^{-1}(Joensuu et al. 1999), whereas Joensuu et al. (2002) reported an average extra export of 268 kg ha^{-1} year^{-1} for the first post-DNM year in 40 DNM areas and Nieminen et al. (2010) about 18-fold higher exports during the first year after DNM than before in nine DNM areas. In the study by Joensuu et al. (1999), the SS concentrations after DNM even exceeded 700-800 mg l^{-1}, which was over 100-fold higher than the average pre-DNM concentration. After the first post-DNM year, high SS exports can still be found, particularly during peak runoffs, such as summer storm flows and snow melt periods in spring (Marttila and Kløve 2010a; Haahti et al. 2016; Tuukkanen et al. 2016).

However, there appears to be considerable variation in the impacts of DNM on SS export, depending particularly on soil characteristics in the ditch banks and bottoms exposed by DNM (Fig. 2). Erosion may be particularly high in sites with such a shallow peat layer, that the ditches reach the mineral soil below the peat layer. Especially fine-textured mineral soils have a high erosion risk after DNM (Fig. 2). Also, the erosion sensitivity of deposited organic sediments in ditches (Marttila and Klöve 2008), ditch bank erosion (Stenberg et al. 2015), as well as the catchment size (Tuukkanen et al. 2012), have been shown to contribute to SS exports from DNM areas. It should also be noted that highly decomposed peats are more sensitive to erosion than slightly decomposed (Tuukkanen et al. 2014).

In areas with fine-textured soils in the exposed ditch banks and bottoms the runoff SS concentrations were found to be higher than before DNM over 20 years, while in coarse textured soils, increased export of SS occurred during the first 1-2 years after DNM (Fig. 2). Joensuu et al. (1999) analysed SS concentrations from 40 DNM areas and determined the textures of mineral soils in their ditch profiles. They presented the following formula for the mean SS concentrations in runoff during the first three years after DNM:

$$C_{ss} = 26.1L_{ft} + 8.73L_{mt} + 4.98L_{ct} + 2.97L_{p} - 14.4 \quad (1)$$

(R^2 = 0.49)

where: C_{ss} = mean concentration of SS in runoff after DNM (mg l^{-1}); L_{ft} = total length of the ditches dug into fine-textured subsoil within each catchment, km; L_{mt} = total length of the ditches dug into medium-textured subsoil, km; L_{ct} = total length of the ditches dug into coarse-textured subsoil, km; L_{p} = total length of the ditches dug into deep peat, km.

Collectively, the different studies indicated that, while the soil and ditch network properties and local hydrology contribute to SS exports after DNM, the possible contact of water with the mineral soil underlying peat dominates SS export. In particular, contact of ditches with medium- and fine-textures mineral soils should be avoided. As the peat layer subsides after drainage, a larger proportion of the ditches may reach the erosion-sensitive mineral soils below peat in DNM than in the first-time, initial drainage. Thus, unless shallower ditches are excavated in DNM than initial drainage, the sediment exports caused by DNM may be much larger than those in initial drainage. This increased risk for high SS exports due to peat subsidence should be considered when planning DNM and choosing the most efficient water quality management structure.

The studies that characterized the quality of SS in runoff from drained peatlands, such as its organic soil content, are scarce (Manninen 1998; Marttila and Klove 2010a; Tuukkanen et al. 2016). In the absence of empirical data, it has been assumed that SS is mostly organic in areas, where the ditch bottoms remain mostly in peat and mineral matter in areas, where the ditches reach the mineral subsoil below peat. The study by Marttila and Kløve (2010a), however, did not support that assumption, since almost 60% of SS was organic in a DNM area, where a large proportion of the exposed soils in the ditches were fine-textured mineral soils (grain size<0.063). Similar results were presented by Tuukkanen et al. (2016) in a DNM area, where organic fraction averaged about 50% of SS. One major reason for the high proportion of organic SS in runoff is its fluffy nature and typical appearance in easily transported flocks. Fine particulate fractions in mineral soils behave in a similar manner, whereas coarser mineral soil particles need considerably more energy for transportation and are deposited more easily near the source areas. Further knowledge on the characteristics of SS exported from DNM areas, such as particle size and organic content, would be essential as SS characteristics determine its transport capacity in the ditch networks and its particulate nutrient concentrations. Furthermore, SS with differing characteristics has very different impacts on aquatic biota (Bilotta and Braziera 2008). Also the role of metal humate colloids (especially Fe) in increasing flocculation and SS exports should be acknowledged (Marttila et al. 2016).

3.3 Exports of dissolved organic carbon

While the initial, first-time drainage can have very variable impacts on DOC (Ahtiainen 1990; Lundin and Bergquist 1990; Rantakari et al. 2010), most DNM studies indicated significantly decreased runoff DOC concentrations (Fig. 3). The decrease in DOC concentrations during the first two years after DNM varied from about 15% in the study by Nieminen et al. (2010) to 30% in one study catchment in Hansen et al. (2013). Joensuu (2013) presented data showing that the pre-DNM DOC concentrations were significantly lower in areas with coarse-textured mineral soils than with peat and medium- or fine-textured mineral soils in the ditch bottoms, and that DNM did not affect DOC concentrations in coarse-textured soils. However, a significant decrease occurred in areas where the ditch bottoms were either medium- and fine-textured mineral soils or peat (Fig. 4). After DNM the DOC concentrations in areas with medium- and fine-textured ditch bottom mineral soils remained lower than before for up to about 20 years. The decrease in DOC exports in kg per DNM-treated area varied from about 40 to 80 kg ha^{-1} $year^{-1}$ during the first few years after DNM (Joensuu et al. 2001; Nieminen et al. 2010; Saari and Högmander 2013), but there are also studies, where DNM had non-significant impacts on carbon exports (Manninen 1995, 1998).

A number of hypotheses have been presented for the likely processes behind decreased DOC exports from DNM areas. A most frequently presented hypothesis is that DNM alters water pathways in such a way that the waters are no longer in close contact with surface peat with high amount of easily releasable, recently dead organic matter. In contrast, the water flow occurs mostly in deep soil layers, where positively charged mineral soil oxohydroxides act as sorption sites for the negatively charged organic moieties (Åström et al. 2001a,b). Negligible changes in organic carbon exports reported by Manninen (1995, 1998) could then be explained by unaltered water pathways as the water table at the studied sites was at a low level already before DNM. That can occur on peatlands with mature tree stands, where evapotranspiration dominates site drainage conditions over the drainage capacity of the ditch network (Sarkkola et al. 2012). Alternatively, DOC exports may not change because the water flow occurs mostly in coarse-textured mineral soil layers below the surface peat (Fig. 4). As a new explanation we propose that the variation in DNM-induced DOC exports between different study sites could also be due to the differing contents of reduction-oxidation sensitive metals in peat. Oxidation of metals along with the water level lowering induced by DNM produces protons, which decrease soil solution pH. At low pH, protonated hydroxyl groups are positively charged, promoting adsorption and surface complex formation with the negatively charged organic molecules, thus decreasing DOC concentrations in soil water. The processes would thus be opposite to those occurring in restored peatlands, where reduction of metals increases soil solution pH and decreases the adsorption of organic moieties (Grybos et al. 2009).

3.4 Exports of N and P

3.4.1 Dissolved N and P

The impacts of DNM may be very different for dissolved than particulate nutrient exports. Both the data sets by Joensuu et al. (2002, 2006) and Nieminen et al. (2010) indicated that DNM has minor impacts on the export of total dissolved nitrogen (TDN). While there was an increase in dissolved inorganic N export, particularly that of ammonium (Joensuu et al. 2002; Hynninen et al. 2011), the dissolved organic N (DON) export decreased (Joensuu et al. 2002), and consequently the TDN export remained largely unchanged (Fig. 5). The decrease in DON export was plausible because its export is affected by the same processes as that of DOC, i.e. either by the decreased production of organic moieties including organic N as a result of water table lowering or by its increased adsorption by positively charged mineral oxohydroxides. However, the TON export in the study by Åström et al.

(2004) did not decrease as much as the exports of TOC, which could indicate that the organic matter released after DNM was enriched with N.

Our review of literature showed contradictory results for the P exports following DNM, as they remained unchanged (Åström et al. 2002), increased (Nieminen et al. 2010), or decreased slightly (Joensuu et al. 2006, Fig. 5). These contradictory results are difficult to explain, particularly those of Åström et al. (2002), who analysed total P (unfiltered samples), the export of which could be expected to increase along with that of SS and adhered particulate P. One factor affecting the variation between studies could be the amount of iron (Fe)-phosphorus minerals in the ditch bottom soils, which can release P-rich Fe phases after DNM (Åström et al. 2002). In addition, the formation of Fe-humic colloids also affects the transport of SS and adhered P (Baken et al. 2016). One more explaining factor for the variable results could be the amount of easily soluble P in the peat, which varies by the fertility of the site (Nieminen and Penttilä 2004). Whatever the mechanisms behind differing behavior of P exports following DNM between the different studies, it should be noted here that the changes in dissolved P export after DNM are generally minor compared to those after other forestry operations on drained peatlands, such as forest harvesting (Kaila et al. 2014) and fertilization (Nieminen and Ahti 1993).

3.4.2 Particulate nutrients

The studies that had the largest data sets on the impacts of DNM on the export of nutrients (Joensuu et al. 1999, 2002; Nieminen et al. 2010) analyzed only the filtered (i.e., dissolved) nutrients. However, there are a few studies where the impacts of DNM on total (unfiltered samples) nutrient exports were analyzed (e.g., Hynninen and Sepponen 1983; Åström et al. 2001a; Marttila and Kløve 2010a,b). Owing to that only three DNM areas were included in these publications, no general conclusions on the impacts of DNM on particulate nutrient exports can be given based on them.

However, the studies by Marttila and Kløve (2010b) and Marttila et al. (2010) indicated that the majority of N and P can be transported in the particulate form, especially during high flow conditions. Thus, particulate nutrient exports should receive more attention in future studies in DNM areas.

To obtain data to estimate how much N and P are exported in particulate form, we collected the solids eroded after DNM and deposited in downstream sedimentation ponds in 12 DNM areas in Finland. Since the different types of eroded soil materials have different rates of deposition, a sample collected from a sedimentation pond may fail to represent an aggregate of the sediments released after DNM. Nevertheless, our analysis showed very high variation in the N and P contents between the different sediment samples. Phosphorus contents ranged from 0.011 to 0.095 % of dry soil, and those of N from 0.09 to 2.15%. This high variation suggests that producing particulate N and P export as the product of SS export and the N and P content of SS is not a straightforward task. Furthermore, we found strong positive correlations between sediment total C and total P, and total C and total N content (Fig. 6), suggesting that ignoring the particulate nutrient exports caused by DNM results in an underestimation of the total N and P exports particularly, where organic matter constitutes a significant proportion of the total SS. As discussed earlier, the organic fraction may generally constitute most of the SS as it is transported more easily than the mineral fraction. Thus, increasing the understanding of the characteristics of SS and particulate nutrient exports are essential in assessing the overall impact of DNM on water quality.

4. Conclusions

By reviewing the available literature, as well as utilizing an existing hydrological model and analysing the characteristics of eroded sediments, we assessed the impacts of DNM on runoff, SS, DOC, N, and

P exports from drained boreal peatland forests. Our review of literature and simulation with the hydrological model both indicated minor impacts of DNM on runoff. The reviewed literature further indicated minor impacts on dissolved N and P exports and decreased rather than increased exports of DOC. Erosion and increased exports of SS and particulate N and P are the most detrimental consequences of DNM in receiving water courses. Particulate N and P exports may reach high levels after DNM particularly, where organic matter constitutes a significant proportion of the total SS. In increasing the understanding of the impacts of DNM on water quality and nutrient and carbon exports, future research should focus on the characteristics of SS and particulate nutrient exports. A major gap in knowledge related to the hydrochemical impacts of DNM is also the very limited climatic and regional representativeness of the studies; 22 of the reviewed 23 papers came from Finnish experiments. High SS exports from the DNM areas with fine- and medium-textured mineral soils in the ditch bottoms suggest that managing ditch depth in such a way that the ditches do not reach the mineral soil below peat would be an efficient means of mitigating SS and adhered particulate nutrient exports.

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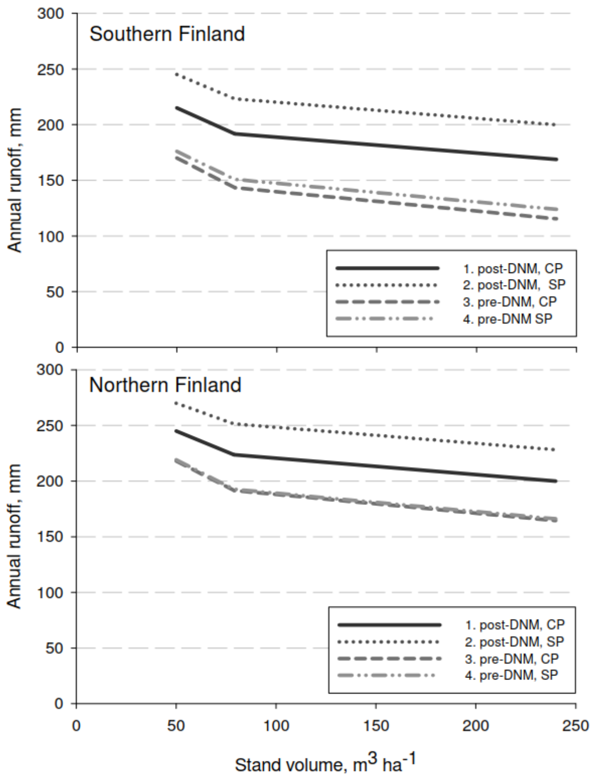

Fig. 1. Annual runoff scenarios for drained Sphagnum (SP) and Carex (CP) peat dominated peatland areas with varying tree stand stem volumes during the first year after DNM as simulated by the FEMMA-model (Koivusalo et al. 2008). The weather input data are as during 2009 in southern (60°27' N; 24°57' E) and northern (64°43' N; 26°0' E) Finland. Pre-DNM and post-DNM ditch depths are 25 and 100 cm, respectively, and ditch spacing is 40 m. The bulk density and hydraulic conductivity of SP are 0.075 g cm^{-3} and 2.12 cm h^{-1}, respectively, and 0.156 g cm^{-3} and 0.58 cm h^{-1} in CP.

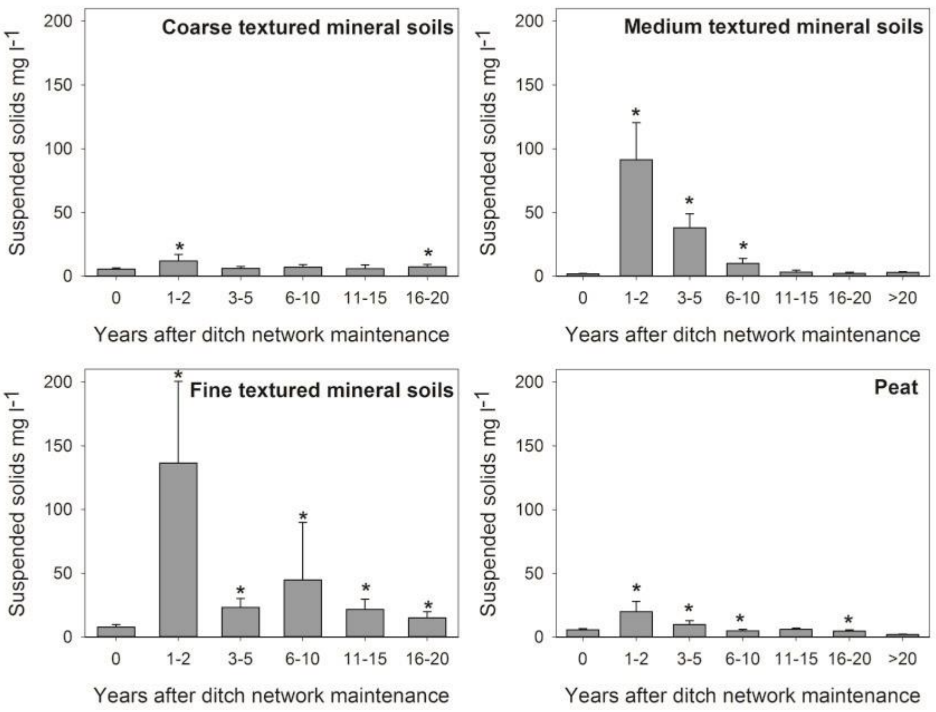

Fig. 2. Mean concentrations of suspended solids ±SE (mg l^{-1}) in ditch outflow water from ditch networks with varying soil characteristics 1-2 years before (year 0) and up to 20 years after DNM. An asterisk indicates statistically ($p<0.05$) significant difference from the pre-DNM period according to Tukey´s HSD-test. Source: Joensuu (2013). Classification of mineral soils in the ditch profiles into different texture classes as in Tamminen and Mälkönen (1999). Fine, medium, and coarse size of mineral soil particles refer to grain size of <0.063 mm, 0.063-0.630 mm, and >0.630 mm, respectively.

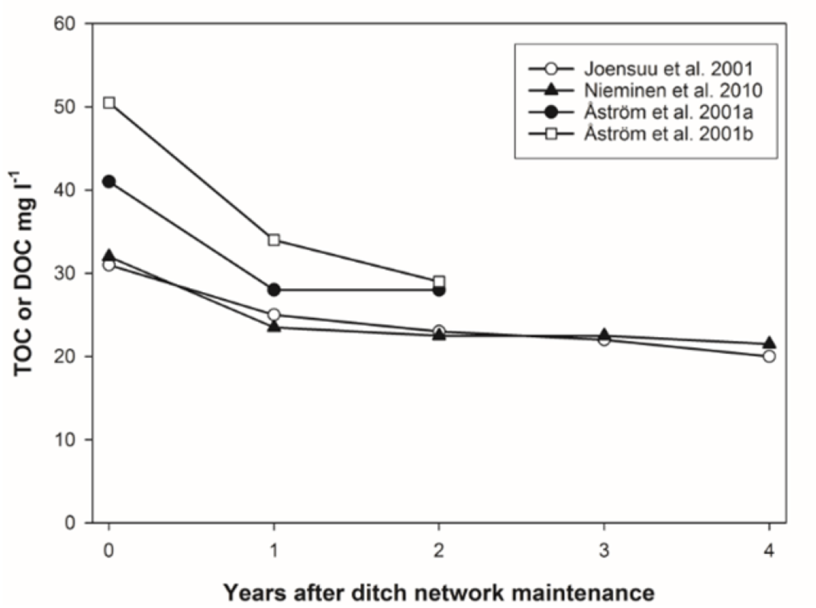

Fig. 3. DOC (Joensuu et al. 2001, Nieminen et al. 2010) and TOC (Åström et al. 2001a, b) concentrations (mg l^{-1}) in ditch-outflow from forestry-drained peatlands 1-3 years before (year 0) and after DNM in the different data sets from Finland. Source: Palviainen and Finér (2013).

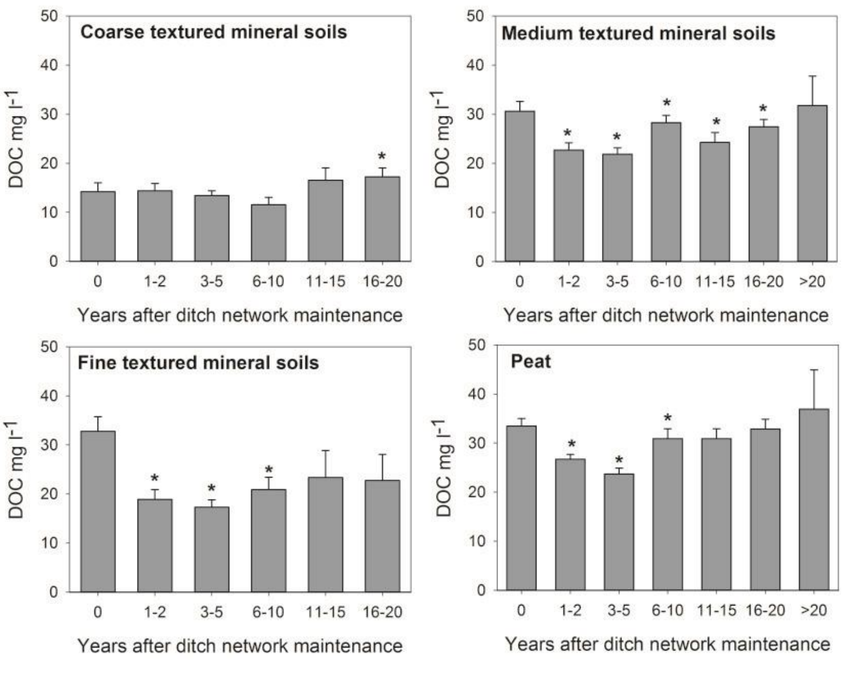

Fig. 4. Mean concentrations of DOC ±SE (mg l^{-1}) in ditch-outflow from drained peatlands with differing post-DNM ditch soil characteristics 1-2 years before (year 0) and up to 20 years after DNM. For further explanation, see Fig. 2.

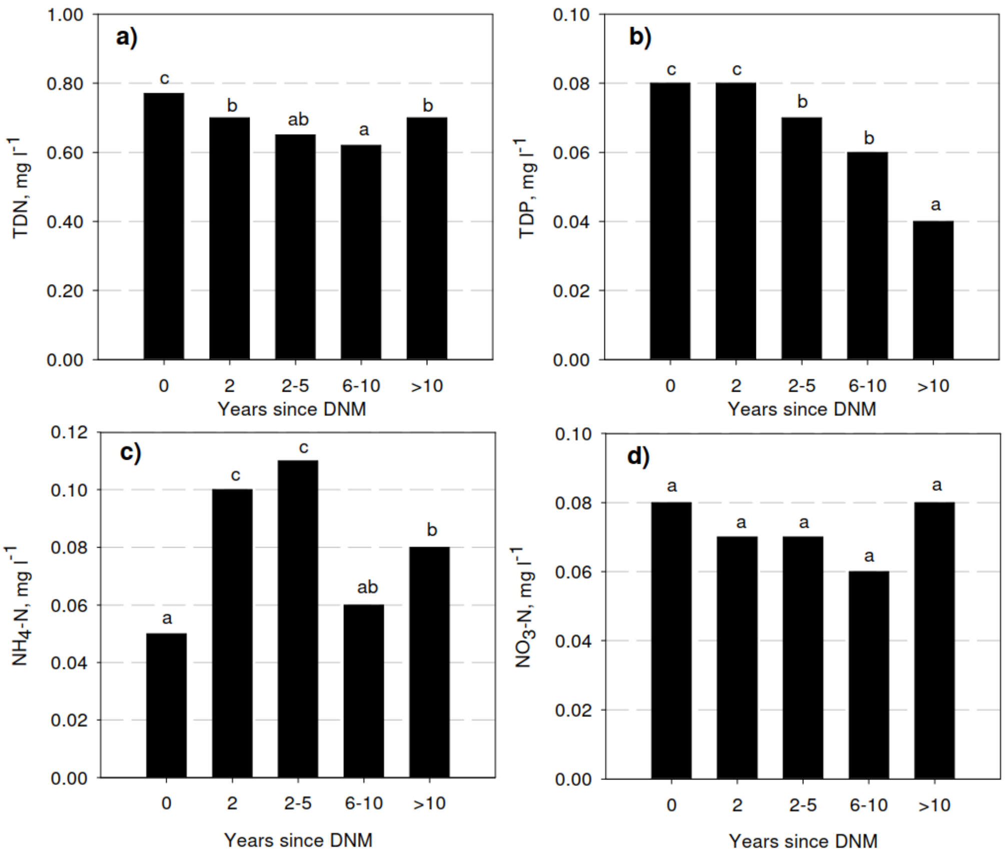

Fig. 5.

Mean concentrations of total dissolved N (TDN), total dissolved P (TDP), dissolved ammonium-nitrogen (NH_4-N), and dissolved nitrate-nitrogen (NO_3-N) 1-2 years before (year 0) and up to >10 years after DNM in 40 catchment areas. Values marked with the same letter are not statistically different ($p<0.05$) according to Tukey´s HSD-test. Redrawn from Joensuu et al. (2006).

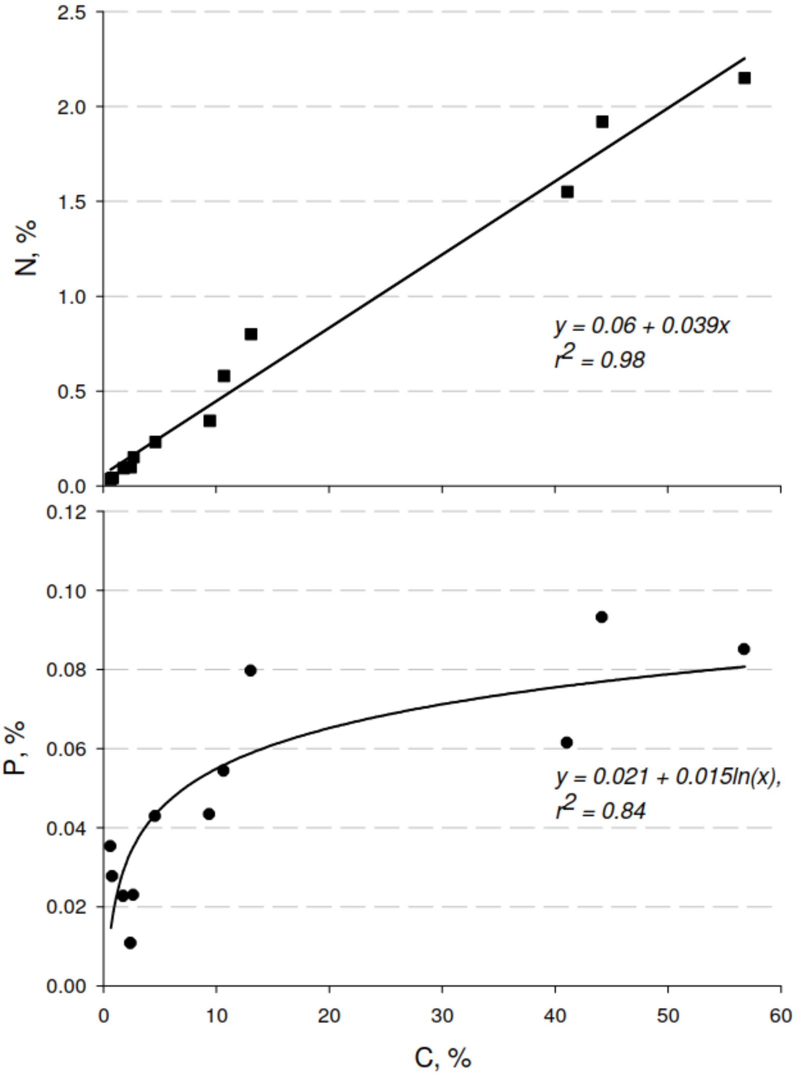

Fig. 6. The relationship between total C (%) and N (%) content, and C (%) and P (%) content in the deposited sediments collected from 12 sedimentation ponds in drained peatland forests in Finland.

Table 1. Characteristics of the reviewed studies on the impacts of DNM on water quantity and quality.

	Study method	Number of catchments (treatment/control)	Study period (years before/ after DNM)	Parameters studied[a)]	Reference
1	Field	1/1	2/2	TOC	Åström et al. (2001a)
2	Field	1/1	2/2	Runoff, SS, TOC	Åström et al. (2001b)
3	Field	1/1	2/2	N, P	Åström et al. (2002)
4	Field	1/1	2/2	N, P	Åström et al. (2004)
5	Modeling	1/0	0/2	SS	Haahti et al. (2016)
6	Field	2/2	2-3/2	SS, N, P	Hansen et al. (2013)
7	Field/Modeling	6/0	1-3/2-4	N	Hynninen et al. (2011)
8	Field	40/0	1-2/>20	SS	Joensuu (2013)
9	Field	37/31	1-2/1-3	SS	Joensuu et al. (1999)
10	Field	23/0	1-2/6	SS, DOC, N, P	Joensuu et al. (2001)
11	Field	40/0	1-2/2-3	SS, DOC, N, P	Joensuu et al. (2002)
12	Field	40/0	1-2/>10	SS, DOC, N, P	Joensuu et al. (2006)
13	Modeling	2/2	6/6	Runoff	Koivusalo et al. (2008)
14	Modeling	1/0	0/2	Runoff, SS	Lappalainen et al. (2010)
17	Field	1/1	4/3	Runoff, SS, N, P	Manninen (1995)
18	Field	1/1	4/3	Runoff, SS, N, P	Manninen (1998)
19	Field	1/0	0/3	Runoff, SS	Marttila and Kløve (2010a)
20	Field	1/0	0/3	Runoff, SS, N, P	Marttila and Kløve (2010b)
21	Field/modeling	9/8	1-3/2-4	SS, N, P	Nieminen et al. (2010)
22	Field	2/1	4-5/2	Runoff, SS	Stenberg et al. (2015)
23	Field	2/2	0.15/2	Runoff, SS	Tuukkanen et al. (2016)

a) Parameters reported in the publications other than runoff, SS, TOC/DOC, N, and P are not mentioned here. N and P may involve their different species, such as total (unfiltered) and dissolved forms, as well as organic and inorganic species.

Table 2. Basic information on the upstream catchment areas of the 12 sedimentation ponds sampled for analysing the characteristics of eroded sediments in DNM areas, and the minerological characteristics of the collected sediment samples. CT = coarse-textured mineral soil, MT = medium textured mineral soil, FT = fine-textured mineral soil. For the samples with both organic (Peat) and inorganic sediment (e.g., CT+Peat), the dominant soil type is given first. For the grain size of CT, MT, and FT, see Fig. 2.

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Pond	Sample minerolog. character.	Upstream area, ha	Location	Climate				Dominant tree species
				Mean annual precip., mm	Mean air temperature, °C			
					Annual	Febr.	July	
1	CT+Peat	87	60°26′N, 23°38′E	663	5.2	-5.7	17.0	Norway spruce
2	FT+Peat	110	61°01′N, 28°19′E	626	3.9	-8.1	17.2	Norway spruce
3	Peat+FT	134	61°14′N, 25°16′E	562	4.1	-7.9	16.8	Norway spruce
4	MT	28	62°02′N, 21°52′E	668	3.7	-6.9	15.9	Scots pine
5	FT+Peat	152	62°12′N, 21°53′E	660	3.5	-7.0	15.8	Scots pine
6	FT+Peat	21	62°16′N, 23°48′E	681	3.2	-7.7	15.5	Norway spruce
7	Peat+FT	172	62°54′N, 26°93′E	637	2.4	-9.5	15.7	Scots pine
8	FT+Peat	47	63°01′N, 26°59′E	637	2.4	-9.5	15.7	Scots pine
9	CT	43	63°27′N, 25°20′E	561	2.4	-9.2	15.8	Scots pine
10	MT	90	64°04′N, 26°40′E	630	2.0	-9.9	15.5	Scots pine
11	CT	102	64°37′N, 27°28′E	630	1.5	-10.0	15.6	Scots pine
12	Peat	102	65°29′N, 27°00′E	589	1.2	-10.6	15.5	Norway spruce