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Impacts of forest harvesting on nutrient, sediment and dissolved organic carbon exports from drained peatlands: A literature review, synthesis and suggestions for the future

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ABSTRACT

We reviewed the studies on the impacts of forest harvesting on nutrient, sediment, and dissolved organic carbon (DOC) exports from drained peatlands with the aim to identify the best practices for mitigation of detrimental water quality impacts. We concluded that so far there are no such practices that would effectively mitigate all harmful consequences of forest harvestings concurrently. Controlling water levels by executing drainage operations immediately after harvesting may decrease the exports of easily soluble and redox-sensitive elements, but the very intensive drainage necessary to lower water levels in highly decomposed peats, as those that typify peats at the clear-felling phase, would result in large exports of sediments and mineral nitrogen. Establishing a wetland buffer area between a forest harvested peatland and the receiving water course may decrease sediment and inorganic nutrient exports, but restored wetland buffers, in particular, may act as a source of DOC and dissolved organic nutrients to receiving water courses. Whole-tree harvesting might decrease nutrient exports in blanket peat areas, but its practical application is hindered by nutritional and forest harvest technology related aspects. We propose that future studies should focus on assessing the impacts of partial harvestings, which so far have received very limited attention.

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1. Introduction

Internationally, around 15 million hectares of peatlands and wetlands were drained for forestry in the temperate and boreal regions, particularly between the 1960s and the late 1980s. Large areas of these forests are now mature and are being or are about to be harvested in the near future. Concerns have been raised about the potential release of sediments, nutrients and dissolved organic matter (DOC) to receiving aquatic systems as a result of harvesting. Peatlands are a major source of DOC and organic nutrients to water courses with higher exports than from mineral soil forests already in their undrained, pristine state (Palviainen et al., 2016).

The concept of harvesting includes a very wide range of forest management practices, and some of the variations in harvesting techniques may have substantial effects on water quality and element exports. The most frequently used method to harvest the trees grown after drainage is clear-felling. Partial harvesting by removing individual mature trees or small groups or strips of trees might lead to smaller nutrient exports than complete harvesting by clear-felling, but the water quality studies assessing the impacts of partial harvesting are scarce. Although thinning is a standard practice to improve silvicultural performance of the remaining trees, particularly in Scandinavian conditions, its impacts on nutrient exports have not been studied. Sebestyen and Verry (2011) studied strip cutting as an alternative to clearcutting on an undrained black spruce bog. To our best knowledge, the study by Lundin (1999) is the only catchment experiment on drained peatland forests that particularly studied the effect of a harvest method (shelterwood cutting) alternative to clear-felling.

Comparison between different studies from drained peatlands is complicated particularly because the presence and intensity of drainage and mechanical site preparation following forest harvesting vary widely. A number of studies have assessed the impacts of harvesting on water quality without drainage or site preparation (e.g., Knighton and Stiegler, 1981; Nieminen, 1998; Rodgers et al., 2010, 2011; Kaila et al., 2015), but draining by ditching (Lundin, 1999) and concurrent draining and site preparation by mound-draining has also been studied (Cummins and Farrell, 2003; Nieminen, 2003).

Management of harvest residues may also vary widely. Modern mechanized harvest practices deposit harvest residues in distinct piles, where the variation in soil temperature and moisture are likely less than in pile-free areas. Nutrient release beneath piles may increase, not only because of increased mineralization of nutrients (Rosén and Lundmark-Thelin, 1987; Asam et al., 2014), but because vegetation re-establishment under piles is restricted and there is no plant uptake to inhibit nutrient leaching. Management of harvest residues may play a particularly large role in nutrient exports in blanket peat catchments in the UK and Ireland. Because of significantly denser and larger stands (>400 m^3 ha^{-1}) at the clear-felling phase than, e.g. Scandinavia, harvest residues in blanket peat catchments may amount to over 80,000 kg (d.w.) ha^{-1} (Asam et al., 2014), which is over four times more than, e.g., Scots pine (*Pinus sylvestris*) dominated stands in Scandinavia (Palviainen and Finér, 2012). In forest operations on blanket peat catchments harvest residues are first used as "brash mats" to improve the soil carrying capacity against heavy harvesting machinery, and as the large amount of harvest residues makes the planting of trees difficult, they are later collected to form "brash windrows", between which the trees are planted. In general, these windrows, each with a width of approximately 4 m, run along the main slope in parallel rows of approximately 12 m (Fig. 1). Frequent machine passes over brash mats may increase their breakdown and thus nutrient mineralization from them, and as the capture of nutrients released from brash mats and windrows by vegetation and soil in brash-free areas is most probably negligible because of overland flow rather than infiltration in the areas of blanket peats with climate of high rainfalls, the practice of managing harvest residues may contribute significantly to nutrient exports.

Fig. 1. Clear-cut blanket peat forest with brash mats (left) and windrows (right) in western Ireland.

Increasing interest in harvest residues as a source of bioenergy has led to peatland forests also being more intensively harvested. Hyvönen et al. (2000) estimated that Norway spruce (*Picea abies*) harvest residues contained 25–31 kg ha^{-1} of P and 245–320 kg ha^{-1} of N, while Carey (1980) reported 46 kg ha^{-1} of P in branches and needles of Sitka spruce (*Picea sitchensis*). Thus, Kaila et al. (2014, 2015) and O'Driscoll et al. (2014a) studied if removal of harvest residues for bioenergy by whole-tree harvesting would be an efficient means to decrease N and P exports. Although stumps are generally not harvested from peatland forests, Kaila et al. (2014), Kiikkilä et al. (2014) and Nieminen et al. (2015a, 2015b) studied stump harvesting along with whole-tree harvesting as one bioenergy harvesting option. The stumps alongside ditches were left unharvested as a precautionary measure to decrease the risk of erosion resulting from the collapse of the ditch banks.

Re-establishment of vegetation and its nutrient uptake after harvesting may be additional factors having a significant contribution to the variation in nutrient exports between different studies. Rapid colonization and flourishing of pioneer species that efficiently retain nutrients, such as cottongrass (*Eriophorum vaginatum*) (Silvan et al., 2004), may act as a substantial sink for the nutrients released from soil and harvest residues. The 5–10 cm thick humus layer consisting mostly of undecomposed needles was regarded as a considerable obstacle for rapid revegetation in blanket peat sites, which is why O'Driscoll et al. (2011, 2014a) studied if seeding native grasses immediately after harvesting would be an efficient means to increase in-situ P uptake and thus reduce P release to receiving water courses.

Variation in soil characteristics has also been shown to contribute to nutrient exports following harvesting. Peats with low aluminium (Al) and iron (Fe) content which occur in nutrient poor ombrotrophic peats and blanket peats have very low P adsorption capacity and thus a high risk for enhanced P exports following harvesting (Cuttle, 1983; Nieminen, 2003; Rodgers et al., 2010), but the contribution of soil characteristics to the export of the other nutrients and DOC from harvested peatland forests is poorly documented.

The presence, type, and intensity of water protection measures may also have a significant contribution to element exports