Forest Ecology and Management 324 (2014) 52–63

Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

Forest harvest effects on mercury in streams and biota in Norwegian boreal catchments

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ARTICLE INFO

Article history:
Received 5 November 2013
Received in revised form 25 March 2014
Accepted 26 March 2014
Available online 19 April 2014

Keywords:
Forest management
Catchment manipulation
Methylmercury
Bioaccumulation
Primary consumers
Clear-cutting

ABSTRACT

Forest harvesting practices can potentially increase mercury run-off from catchments. A paired catchment experiment was conducted in a boreal forest in southern Norway, to test effects of forest harvest operations on (i) concentrations and fluxes of methylmercury (MeHg), total mercury (HgT), nutrients and dissolved organic matter (TOC), and on (ii) MeHg bioaccumulation in stream foodwebs.

Thirty percent of a catchment was harvested in winter time with snow cover but no soil frost, resulting in wheel tracks and soil compaction. Pre-harvest differences included higher streamwater MeHg, HgT and TOC, and lower pH in the treated catchment compared to the reference.

No significant treatment effects on concentrations of MeHg, HgT and TOC were detected, whereas concentrations of nutrients (ammonium, nitrate, phosphorus (P)) increased significantly. Estimated catchment export of nitrate and ammonium increased fourfold, as a combined effect of changed discharge and concentrations. Export of MeHg and HgT increased weakly, primarily because of an increase in discharge.

Levels of MeHg in stream invertebrates mirrored differences in aquatic MeHg between the two streams, resulting in higher MeHg in biota in the harvest catchment in pre-harvest conditions. After harvest, MeHg levels in primary consumers (herbivorous stoneflies) were no longer different between the two streams, despite continued exposure to higher aqueous MeHg in the harvested catchment. Simultaneously, dietary biomarkers (δ^{15}N signature, lipid- and algal fatty acid content) in the stoneflies had changed significantly, consistent with higher nutrient loadings and associated higher diet availability in the harvested stream.

The results of our experiment do not support that forest management has a strong impact on catchment MeHg production. Catchment disturbance through forest harvesting may decrease MeHg in aquatic biota, because of higher stream productivity and associated higher quality of dietary sources, at least in the short-term. Other studies on catchment MeHg production to disturbance have shown a range in responses, from strong to none. So far, no factor has emerged to explain such range in responses. Predictions of forest management effects on MeHg in streamwater and aquatic food webs are hampered by limited understanding of catchment controls on MeHg production.

1. Introduction

Mercury (Hg) is a long-range transported pollutant of great environmental concern in boreal areas across the entire northern hemisphere. Atmospheric deposition of Hg in natural ecosystems leads to long-term accumulation of Hg in soils and wetlands, where transformations of Hg to its highly toxic organic form methylmercury (MeHg) occur with subsequent transport of Hg-species to surface waters (Grigal, 2002). MeHg is a neurotoxin with a strong tendency to bioaccumulate in food webs (Morel et al., 1998). Levels of MeHg in the aquatic food web are raised to levels that are potentially harmful for fish and wildlife (Scheulhammer et al., 2007) and, through consumption of fish, to human health (Mergler et al., 2007).

High Hg concentrations in fish are associated with brown-water streams and lakes in forested regions with a prevalence of

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http://dx.doi.org/10.1016/j.foreco.2014.03.044
0378-1127/

wetlands (Nilsson and Håkanson, 1992; Driscoll et al., 2007; Chasar et al., 2009). Wetlands are commonly viewed as one of the main suppliers of MeHg to aquatic ecosystems, because of high groundwater levels, creating anoxia and thereby promoting conditions for methylation of Hg (Grigal, 2003). Not just wetlands, but also forests have the potential to be a significant source of MeHg to surface waters. Coniferous forests are highly effective scavengers for atmospheric Hg species, resulting in substantially higher Hg deposition in forests compared to open areas (Graydon et al., 2008; Witt et al., 2009), thereby enriching forest soils with Hg. Forest throughfall has been shown to be a significant input of MeHg to boreal catchments (Witt et al., 2009), possibly demonstrating an additional pathway of MeHg from forest canopies to surface waters.

Recently, forest management has been suggested to be an important contributor to catchment export of MeHg, thereby increasing MeHg in the aquatic food chain (Bishop et al., 2009). Forests in northern Europe (Ostlund et al., 1997) and large parts of North America (Stinson et al., 2011) are landscapes where forest management practices have left a strong mark. Because of increased interest in the role of forest for climate mitigation (Jackson et al., 2008), especially as a source of bioenergy (Schlamadinger and Marland, 1996), forest management might intensify. Thus, further assessment of environmental impacts of forest harvest practices is needed to protect aquatic ecosystems.

Forest harvesting is known to have a strong impact on catchment hydrology and nutrient runoff (Likens et al., 1970; Kreutzweiser et al., 2008). Effects of forest harvesting and soil disturbance on MeHg runoff have been shown in Finland (Porvari et al., 2003) and Sweden (Munthe and Hultberg, 2004). However, the mechanisms controlling the increased export of MeHg are not well understood. Soil disturbance with associated increases in mobilization of MeHg from soil pools has been hypothesized previously as controlling mechanism (Munthe and Hultberg, 2004), in addition to increased discharge, changed hydrological pathways and higher soil temperatures (Porvari et al., 2003; Eklof et al., 2013). Still, forest operations have not lead to increases in MeHg runoff in all cases. No effect of harvest operation on MeHg runoff was found in catchment manipulations in Sweden, despite small increases in runoff (Sorensen et al., 2009a) and extensive damage to soils from forest machinery (Sorensen et al., 2009a; Eklof et al., 2013).

Another type of evidence for relations between forest management and MeHg in aquatic ecosystems comes from synoptic studies. Studies of lake ecosystems in Canada indicated a connection between catchment disturbance and increased levels of MeHg in the aquatic food web (Garcia and Carignan, 1999, 2000; Desrosiers et al., 2006; Garcia et al., 2007). Here, increased levels of MeHg in aquatic biota and periphyton were related to catchment disturbance, while aqueous dissolved MeHg was not investigated. Further, significant relations between MeHg in aquatic biota and dissolved MeHg in waters were found by Hall et al. (2009) in Canadian flooded reservoirs, and by Chasar et al. (2009) in a synoptic study of stream foodwebs in the United States. Thus, relations between catchment disturbance and enhanced levels of MeHg in biota have been implied, but are not well-documented. In addition, the limited number of studies and lack of consistent responses of forest management on MeHg export indicate a strong need for a better understanding of processes underlying catchment MeHg production from experimental settings.

In order to test the hypothesis that forest harvest (i) increases streamwater MeHg and total Hg concentrations and runoff, and (ii) enhances MeHg concentrations in biota, we conducted a paired-catchment study in a Norwegian boreal forest. Streamwater chemistry, hydrology and levels of MeHg in stream invertebrates were investigated, including links between diet and bioaccumulation of MeHg.

2. Materials and methods

2.1. Site description

The Langtjern study area is located in southeast Norway (60°37′N, 9°73′E) at 500–710 m elevation approximately 80 km northwest of Oslo (Fig. 1). The Langtjern lake catchment is part of the national monitoring programme for effects of acid deposition and consists of two inlet streams and a lake outlet, where streamwater chemistry and discharge have been monitored since 1972. The eastern inlet stream catchment (LAE03) was used as the reference catchment. The treatment catchment (LAE11) is located 1.5 km southeast of LAE03, adjacent to the lake catchment, and is slightly less than one-third of the size of the LAE03 catchment (Table 1).

Mean annual discharge from the Langtjern lake outlet between 2008 and 2011 was 702 mm, while mean annual precipitation and temperature were 914 mm and 4.5 °C, respectively (nearby meteorological station Gulsvik II, 132 m elevation, 60°38′N, 9°60′E). Wet sulphur (S) deposition was 5 kg S ha^{-1} in 1990 (Larssen, 2005) and 3 kg S ha^{-1} in 2000 (De Wit et al., 2007) respectively and is still declining.

The vegetation at Langtjern is dominated by low- to unproductive Scots pine forest (*Pinus sylvestris* L.), interspersed with peatlands (both forested and open Sphagnum mires) and patches of Norway spruce (*Picea abies* (L.) Karst.) forest. The stands are mature or close to maturity. The geology consists of till of felsic gneisses and granites, where thin mineral soils have developed. Deeper peaty soils are found, being most abundant close to streams. The area proportion of main forest- and vegetation types is similar in the two catchments, the most notable difference being a higher percentage of forested peatland (forest on peat soils of at least 30 cm depth) in the LAE11 catchment. In LAE11, pre-treatment volume proportions of Scots pine, Norway spruce and birch were 57%, 34% and 9%, respectively, while the corresponding numbers were 62%, 35% and 3% in LAE03. LAE03 and LAE11 had a stocking of 78 and 62 m^3 ha^{-1}, respectively. These volumes illustrate the low site productivity of the study area.

2.2. Experimental design and harvest operation

The paired catchment experiment consisted of two small forested catchments, the reference (LAE03) and the treatment catchment (LAE11). Monitoring started in June 2008. The forest harvest operation in the LAE11 catchment was conducted from January 13 to 16 in 2009. Forest standing volume, water chemistry, discharge and aquatic biota were monitored before and after the harvesting operation. The choice for the timing of the harvest operation and thereby the length of the pre-harvest treatment was partly based on the original period of project funding, i.e. three years.

The harvesting operation was done using the ‘cut to length’ method (harvester and forwarder). The impacted area was confined to the lower and middle part of the LAE11 catchment, affecting about 30% of the catchment area and with a harvest removal corresponding to 38% of total catchment tree volume. As the forwarder would have to cross several areas with limited bearing capacity on its route between the harvested area and the landing site the harvesting operation was scheduled to take place in winter, when the soil was expected to be frozen. However, due to mild weather prior to harvest, the soil was not frozen. Snow depth was circa 20 cm during harvesting. Thus, harvesting resulted in local soil disturbance in the form of wheel ruts. This was most pronounced along the main extraction tracks and in wetter parts adjacent to the stream in the lower part of the catchment, while the upland parts of the catchment area were less affected. Norwegian