

Nitrogen export from a boreal stream network following forest harvesting

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Nitrogen export from a boreal stream network following forest harvesting: seasonal nitrate removal and conservative export of organic forms

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Abstract

Boreal streams are under pressure from large scale disturbance by forestry. Recent scenarios predict an increase in forest production in Scandinavia to meet market demands and to mitigate higher anthropogenic CO₂ emissions. Increased fertilization and shorter forest rotations are anticipated which will likely enhance the pressure on boreal streams in the near future. Among the major environmental impacts of forest harvesting is the increased mobilization of inorganic nitrogen (N), primarily as nitrate (NO₃⁻) into surface waters. But whereas NO₃⁻ inputs to first-order streams have been previously described, their downstream fate and impact is not well understood. We evaluated the downstream fate of N inputs in a boreal landscape that has been altered by forest harvests over a 10 year period to estimate the effects of multiple clear-cuts on aquatic N export in a boreal stream network. Small streams showed substantial leaching of NO₃⁻ in response to harvests with concentrations increasing by ~ 15 fold. NO₃⁻ concentrations at two sampling stations further downstream in the network were strongly seasonal and increased significantly in response to harvesting at the medium size, but not at the larger stream. Nitrate removal efficiency, E_r , calculated as the percentage of “forestry derived” NO₃⁻ that was retained within the landscape using a mass balance model was highest during the snow melt season followed by the growing season, but declined continuously throughout the dormant season. In contrast, export of organic N from the landscape indicated little removal and was essentially conservative. Overall, net removal of NO₃⁻ between 2008 and 2011 accounted for ~ 70 % of the total NO₃⁻ mass exported from harvested patches distributed across the landscape. These results highlight the capacity and limitation of N-limited terrestrial and aquatic ecosystems to buffer inorganic N mobilization that arises from multiple clear-cuts within meso-scale boreal watersheds.

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1 Introduction

Decades of research have shown that disturbance of forest ecosystems can lead to increased losses of inorganic nitrogen (N) from land (Vitousek et al., 1979; Likens and Bormann, 1995; Aber et al., 2002; Houlton et al., 2003), with potentially negative consequences for water quality in streams and rivers (Martin et al., 2000). Perhaps the clearest demonstrations of how forest disturbance influences terrestrial nutrient mobilization have used experimental harvests in small catchments to document changes in stream chemistry relative to undisturbed controls (Likens et al., 1970; Swank and Vose, 1997). While the magnitude and duration of response to harvest varies among studies (Binkley and Brown, 1993; Kreuzweiser et al., 2008), most have documented increases in stream-water nitrate (NO_3^-) concentrations. Such responses reflect the loss of plant nutrient demand (Boring et al., 1981), accelerated rates of soil N mineralization and nitrification (Holmes and Zak, 1999), and increases in hydrologic flux within the catchment (Hornbeck et al., 1997; Andréassian, 2004). By design, the majority of this research has addressed responses to forest disturbance at small spatial scales (e.g., catchments of first-order streams) but has not explored how localized increases in nutrient concentration are translated downstream within fluvial networks.

Whereas studies have addressed the removal of inorganic N at the network scale (Helton et al., 2011; Wollheim et al., 2006; Worrall et al., 2012; Alexander et al., 2009), little has been done to investigate the specific effects of forestry on nitrogen cycling in boreal stream networks. A clearer understanding of how the enrichment of headwater environments through forestry is expressed at larger spatial scales (Futter et al., 2010) is important if policy makers are to consider the broader biogeochemical implications of forest management.

The degree to which surplus NO_3^- derived from forest disturbance is delivered to downstream receiving systems is determined by the balance between hydrologic transport and biological demand within multiple habitats at the terrestrial–aquatic interface (McClain et al., 2003; Seitzinger et al., 2006). For example, when forest harvesting

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~ 10 m wide at each stream side, discontinuous riparian buffer was left intact at NO-5. All clear-cuts in the network were performed as final-fellings for commercial purposes following environmental considerations according to the Swedish Forestry Act, interpreted and applied by the forest owner. Thus leaving small (5–10 m) buffer zones along headwater streams is common practice.

2.2 Stream water chemistry

Concentrations of NO_3^- and dissolved organic nitrogen (DON) were determined from unfiltered stream water samples. As fractions of particulate organic matter are generally very low in this landscape (< 0.6%; see Laudon et al., 2011) we consider samples to represent dissolved solute concentrations. Samples were collected between 2004 and 2012 at one to two week intervals during spring, summer, and fall, and at four week intervals during winter low flow. Samples were frozen within 1–2 days after collection and analyzed using colorimetric methods at a SWEDAC accredited laboratory according to method SS-EN ISO 13395:1996 for NO_3^- (sulphanil amid method after cadmium reduction), according to Bran & Luebbe Method G-171–96 Rev. 1 (Phenate method) for ammonium (NH_4^+), and method SS-EN 12260:2004 for total N (combustion to nitrous oxide followed by chemiluminescence detection) (Löfgren et al., 2009). Thus, reported concentrations of NO_3^- equal the sum of nitrate and nitrite expressed as mass of N (μgNL^{-1}); concentrations for DON were calculated as total N minus inorganic N. Analysis uncertainty for NO_3^- were 5% for the concentrations range of 1–100 μgL^{-1} and 4% for 100–1000 μgL^{-1} ; uncertainties for NH_4^+ were reported as 14% for 3–20 μgL^{-1} and 8% for 20–100 μgL^{-1} . Uncertainties for total N were 14% for 50–1000 μgL^{-1} and 8% for 1–5 mgL^{-1} .

2.3 Mixing model

We used a mixing model to represent the landscape mass-balance for NO_3^- and DON. This model assumes conservative mixing as well as conservative mass transport of wa-

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ter and solutes from two landscape end-members (EMs): clear-cuts and control forests. The chemistry at downstream stations (BA-1 and BA-2) can then be predicted from the simple mixing of the hydro-chemical signal from the upstream EMs. The percentage of clear-cut area of each sub-catchment was derived from high-resolution satellite images supplied by the Swedish Forest Agency combined with local ground-truthing (see Schelker et al. (2014) for a full description). This data comprises all clear-cuts from the past 10 years (2002–2012, see also Fig. 1). Similar to earlier work, we considered harvest prior to this period to have a negligible effect, due to their low spatial extent in the watershed (Schelker et al., 2014). Thus, the remaining area was assumed to constitute entirely uncut forest.

The concentration at a downstream location (C_{modelled} , in mg L^{-1}) for each time step was modeled using the area specific mass export (Eq. 1):

$$C_{\text{modelled}} = (M_{\text{harvest}}A_{\text{harvest}} + M_{\text{control}}A_{\text{control}})Q_{\text{out}}^{-1} \quad (1)$$

with Q_{out} being the specific discharge (mm day^{-1}) at the downstream site, M_i ($\text{mg m}^{-2} \text{day}^{-1}$) being solute mass export for the site i ($i = \text{harvest, control}$). M_i was calculated as $M_i = Q_i C_i$, with C_i (mg L^{-1}) being the solute concentration and Q_i (mm day^{-1}) being the discharge. A_i (%) was the percentage of the total area that was harvested or acts as a control for the site i , respectively. This mass-balance model allows simulating the contributions of clear-cuts vs. control forests to downstream sites by considering the changes in solute concentrations and water discharge.

A 100 % harvested catchment did not exist in Balsjö and N leakage into first-order streams following clear-cutting may vary dependent on local factors, such as the presence of riparian forest buffers (Laurén et al., 2005), and was also observed to differ between the two harvested sites in Balsjö (Löfgren et al., 2009). Thus we calculated C_{harvest} (mg L^{-1}) in Eq. (1) for each time step as the average concentration of CC-4 and the NO-5 northern catchment, each scaled to 100 % harvest using a scaling equation. This equation extrapolates the difference between observed concentration ($C_{\text{obs},j}$, in mg L^{-1} with $j = \text{CC-4 or NO-5}$) and the concentration of the control forest EM, C_{control}

at RS-3 did not show such a seasonal pattern, suggesting particularly low inorganic N availability and strong N-limitation persisting throughout the year (Stoddard, 1994). This hypothesis is further supported by the fact that average NO_3^- concentrations at this site decreased significantly by $-6.5 \mu\text{gNL}^{-1}$ between the pre-treatment and the treatment period, indicating that local factors, such as the presence of actively growing forest stands with dense riparian vegetation, resulted in a high inorganic N demand and thus low stream concentrations at this site.

Seasonal variations in NO_3^- concentrations at the CC-4 clear-cut during the dormant season (Fig. 2) were related closely with temporal changes in NO_3^- concentration at the downstream sites (Fig. SS1), indicating a temporal coherence in concentration change (sensu Kling et al., 2000) within the network. Overall, these observations suggest (i) a common seasonal control where NO_3^- retention in most catchments declines throughout the dormant season, (ii) that enhanced upstream inputs of NO_3^- in headwaters are translated downstream during the dormant season, and (iii) that temporal nutrient dynamics at upstream and downstream reaches become uncoupled during the spring and the summer growing season.

Poor relationships between measured and modelled NO_3^- concentrations at BA-1 and BA-2 (Fig. 3, data for BA-2 not shown) are likely to result from seasonal NO_3^- removal, a pattern supported by the temporal variation of E_r for both sites (Fig. 4). In contrast, the relationships of modelled and measured DON concentrations are similar to those previously observed for dissolved organic carbon, as well as the two conservative tracers, dissolved silica and chloride (Schelker et al., 2014). These relationships are thus indicative for an approximately conservative downstream transport of DON in the network. Furthermore, these patterns provide additional support for the applicability of our mixing model in this landscape, as they are consistent with the idea that bulk DON is composed primarily of organic compounds of low bioavailability that is exported from landscapes without strong biotic controls (Hedin et al., 1995). For this reason, DON also often represents the major loss vector for N in catchments that are not subject to large anthropogenic inputs of inorganic N (Perakis, 2002; Kortelainen

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et al., 1997). Given that clear cutting led to increased DOC export from these same catchments (Schelker et al., 2014), and that DOC and DON are assumed to belong to the same organic matter pool and are thus often highly correlated in boreal catchments (Sponseller et al., 2014), losses of DON in response to harvesting may represent an important and largely unappreciated source of terrestrially derived N to downstream receiving systems (Rosén et al., 1996).

Low dormant season values of E_r suggest an ostensibly weak NO_3^- demand in cold, snow-covered streams and thus low strength of the biological sink within the fluvial network. During this period a large fraction of NO_3^- entering the stream network was also exported downstream, which is exemplified by the few wintertime occasions where E_r was near-zero. These occasions suggest that either (i) all NO_3^- was transported downstream (e.g. that NO_3^- transport was conservative) or (ii) that the downstream reaches of the stream network acted as source areas of NO_3^- . The latter has been previously hypothesized to cause discrepancies of reach scale N mass-balances (von Schiller et al., 2011).

Interestingly, E_r did not show a direct dependence on stream discharge at any of the downstream sites (Fig. 4), suggesting that N-demand rather than flow (Hill, 1993) and/or transient storage (Ensign and Doyle, 2006) were controlling NO_3^- removal in the fluvial network. In addition, high removal efficiencies during spring and summer had substantial effects on overall annual net NO_3^- removal as estimated by the difference of modeled and measured annual NO_3^- exports. These estimates (\pm SD) showed that 71(\pm 4) % and 67(\pm 10) % of the NO_3^- inputs to the BA-1 and BA-2 catchments were removed before reaching the outlets (Table 1).

Furthermore, our estimates of net NO_3^- removal suggest that during most periods, reasonable levels of in-stream activity could account for the discrepancy between measured and modeled fluxes at downstream stations. Assuming that all NO_3^- retention was occurring within the stream channels, median values and interquartile ranges (10th to 90th percentile) for the BA-2 catchment were -5.8 (-21.9 ; -1.3) $\mu\text{g N m}^{-2} \text{min}^{-1}$ for the entire year. These values fall well within the range of net uptake estimates made else-

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of the year would then limit heterotroph turnover of DOM – a coupling that has been suggested previously for boreal streams (Berggren et al., 2007).

In summary our work agrees with earlier studies in that terrestrial ecosystem disturbance enhances NO_3^- mobilization into first-order streams (Likens et al., 1970) and that such increased NO_3^- concentrations can potentially be transferred downstream (Alexander et al., 2007). The hypothesis that stream and riparian processing of NO_3^- may dampen the effect at downstream sites (Bernhardt et al., 2003) was supported during the snow melt, as well as during the growing season when rates of biological activity and supply of bioavailable C are likely to be high. During the dormant season, however, results suggest that limited net NO_3^- uptake rates constrain the potential for NO_3^- removal within the fluvial network. Considering the two mentioned measures to increase forest production (Egnell et al., 2011), we argue that both are likely to increase downstream export of NO_3^- , if the stream network's removal rates remain the same as under current conditions. More specifically, shorter forest rotations would increase the frequency of disturbance due to harvesting and thus the periods where elevated leaching may occur. Similarly, increased fertilization may enhance the risk of NO_3^- leakage into surface waters particularly during the dormant season (Binkley et al., 1999) when the biological demand for inorganic N is low within boreal stream networks.

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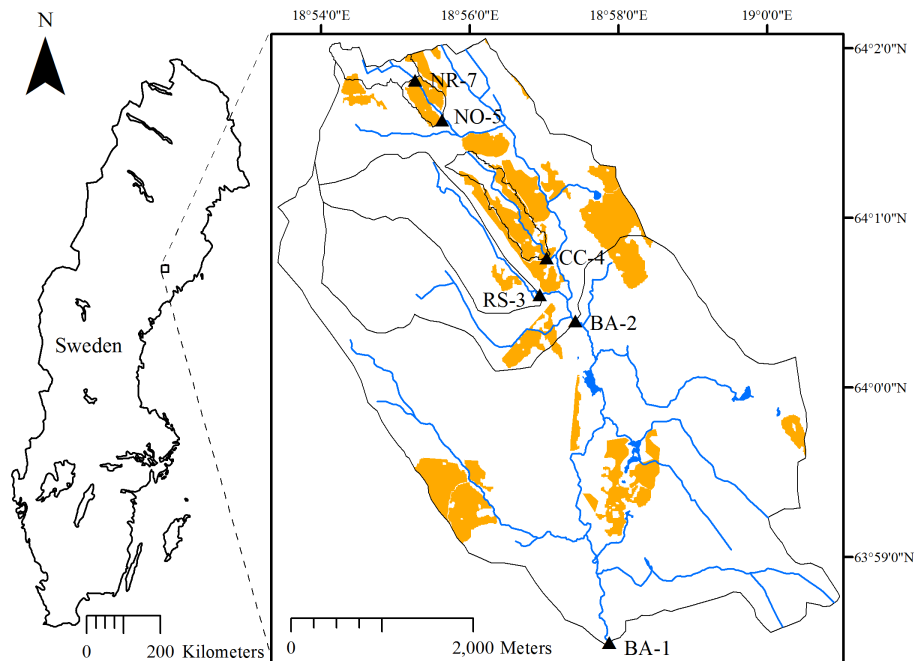


Figure 1. The “Balsjö Paired Catchment Experiment” including the catchments RS-3, CC-4, NO-5 and NR-7, as well as the two downstream sites BA-2 and BA-1 that integrate the larger 22.9 km² Balsjö Stream Network. Areas harvested during 2001–2011 are shown as orange. Solid blue lines represent the stream network; solid blue areas show ponds with open water. Solid black lines indicate the catchment boundaries, black pyramids the location of water sampling.

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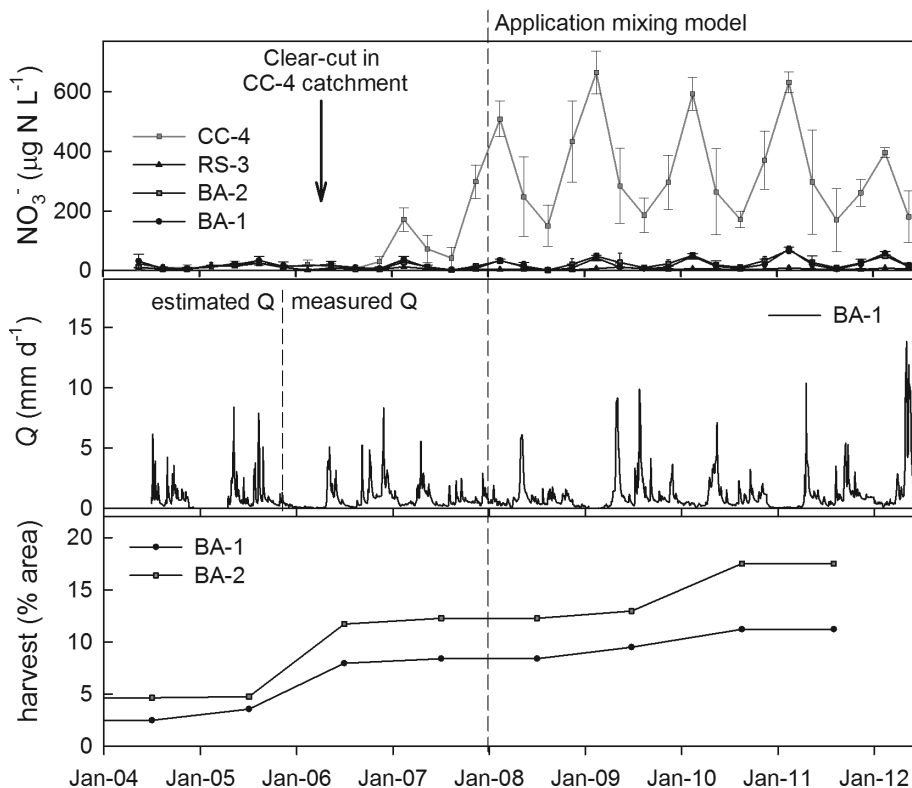


Figure 2. First Panel: trimonthly nitrate (NO_3^-) concentrations and standard deviations (whiskers) of two first-order streams, the clear-cut catchment (CC-4) and the reference south (RS-3), as well as for two third-order downstream sites BA-2 (size = 8.7 km^2) and BA-1 (size = 22.9 km^2). Second panel: discharge at the BA-1 outlet. Third panel: satellite derived percentage of catchment area that has been clear-cut harvested since 2001 within BA-2 and BA-1.

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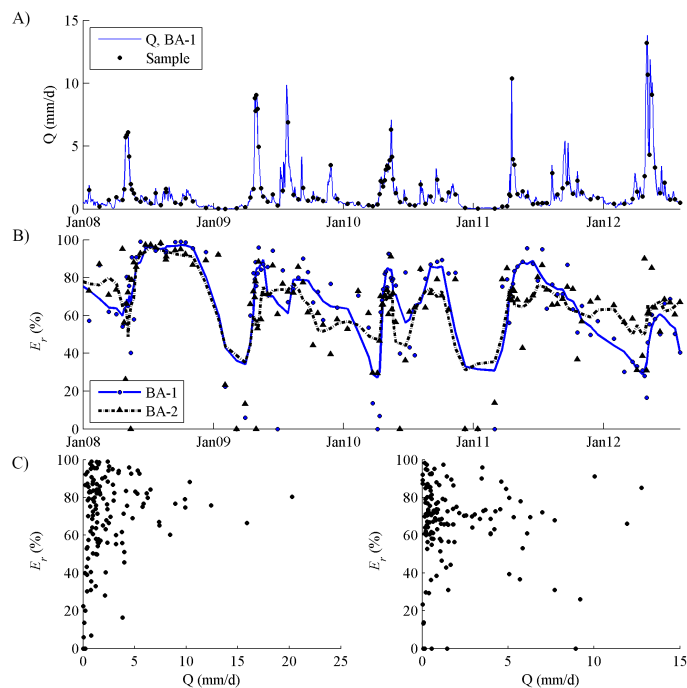


Figure 4. , Panel (a): Stream discharge (Q) and sample drawing at the BA-1 site. Panel (b): Seasonal variation in NO_3^- removal efficiency (E_r), that is, the difference between measured and modeled NO_3^- concentration divided by the modeled concentration for the two downstream sites BA-1 and BA-2; lines represent moving averages with $n = 5$. Panel (c): E_r vs. Q for the BA-1 (left) and the BA-2 (right) catchment outlets, respectively indicating little dependency of E_r on Q at both sites.

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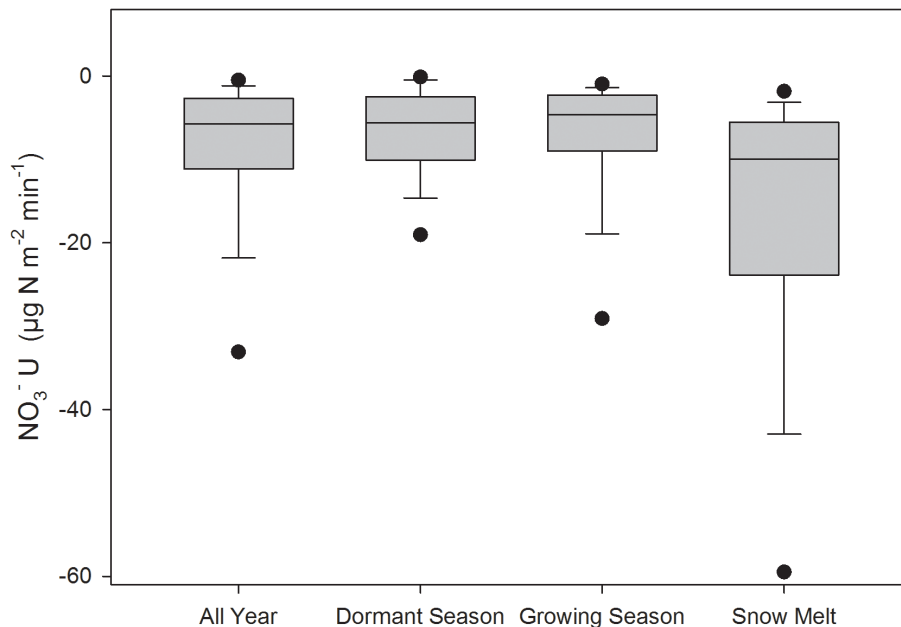


Figure 5. Boxplot of the seasonal differences in net NO_3^- uptake rates (U) per unit stream area during 2008–2011 in the BA-2 catchment. Solid lines represent median values, boxes the 25th to 75th percentile range, whiskers the 90th to 10th percentiles and dots the 95th and the 5th percentiles. Pairs of letters indicate highly significant differences between seasons ($p < 0.001$; Mann–Whitney Rank Sum Test). Values for BA-1 site are generally lower, but show similar seasonal differences.

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