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Nitrogen fluxes after clear-cutting. Ground vegetation uptake and stump/root immobilisation reduce N leaching after experimental liming, acidification and N fertilisation

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ABSTRACT

Clear-cutting often results in a dramatic change in the soil nitrogen (N) balance. This study analysed the fate of inorganic soil N over four years (1992–1995) in a new clear-cut containing three replicate blocks. Treatments comprised control (0), 6000 kg $CaCO_3$ ha^{-1} (Ca), 600 kg sulphur powder ha^{-1} (S) and 600 kg urea-N ha^{-1} (U), applied during 1976–1987 to a Norway spruce (*Picea abies*) forest. Trees were cut in March 1992, after which stems, tops and branches were removed from the 12 experimental plots. Spruce seedlings were planted in May 1992. Clear-cutting resulted in accumulation of approx. 50 kg inorganic N ha^{-1} in the 30 cm deep topsoil of the 0, S and U treatments and 25 kg N ha^{-1} in the Ca treatment by October of 1992. During the next two years, the inorganic pools increased (S), stabilised (0 and U) or declined (Ca), but from the end of the third year all inorganic pools decreased. Plant cover gradually increased with dominance of *Deschampsia flexuosa*. Mean plant N uptake in grasses, forbs and spruce seedlings was estimated at 95 (0), 139 (Ca), 52 (S) and 121 (U) kg N ha^{-1} for the four-year period. Nitrogen leaching at 50 cm depth was dominated by NO_3–N and culminated during the second (Ca and U) and third (0 and S) years. Cumulative N leaching for the four-year period was lower for U and Ca (28 and 31 kg N ha^{-1}) than for 0 and S (53 and 81 kg N ha^{-1}), and was inversely correlated with plant N uptake. Nitrogen immobilisation in stumps and root necromass (including spruce and grass roots) was calculated to be 35–45 kg N ha^{-1} during this period. The four-year N balance showed 5–17% higher inputs (net mineralisation and deposition) than outputs (plant uptake, leaching, immobilisation in dead stumps/roots and accumulation of inorganic N). Gaseous N losses were not studied, but high pH and high NO_3^-–N formation in the organic layers of the Ca treatment in 1992 might have favoured denitrification, which can partly explain the lower amount of inorganic N remaining in this treatment. A novel finding was that stump and dead root immobilisation of N was quantitatively important. A second novel finding was that lime application, although stimulating nitrification, also stimulated plant N uptake so much that nitrate leaching was reduced in comparison with the control and sulphur treatments.

1. Introduction

Clear-cutting is the dominant forest regeneration method in many parts of the world and involves felling and removal of all tree stems in a stand. It causes disturbance of the forest ecosystem, in particular nitrogen (N) cycling. Because root uptake ceases, ongoing N mineralisation results in accumulation of inorganic N [ammonium–N (NH_4–N) and nitrate–N (NO_3–N)] in the soil. Increased NH_4–N levels in the soil stimulate formation of nitrate, which is easily leachable and can reach groundwater and streams (Likens et al., 1970; Smolander et al., 1998; Ring et al., 2003; Titus et al., 2006). Leaching of inorganic N after clear-cutting normally lasts for five years, with a peak after 1–2 years (Huber et al., 2004; Hedwall et al., 2013). The peak concentration of nitrate N in the soil solution can vary from below 0.5 mg L^{-1} (Berdén et al., 1997) to 30 mg L^{-1} (Huber et al., 2006).

Tree growth in northern coniferous forest ecosystems is normally N-limited. This explains why N fertilisation is a common practice to improve forest production in these systems (Ring

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et al., 2003). Clear-cutting of previously fertilised stands can result in increasing N leaching with increasing doses of fertiliser N (Ring, 1996), but even high doses of fertiliser N do not necessarily increase N leaching after clear-cutting when combined with a fertiliser mix with, for example, phosphorus and potassium that are needed for optimum plant growth (Bergh et al., 1999; Hedwall et al., 2013).

Liming has been suggested as a means to counteract soil acidification in acidic forest soils. It can increase nitrate leaching in N-rich soils (Huber et al., 2006), but it does not seem to increase the nitrification potential after clear-cutting in N-poor soils (Smolander et al., 1998).

Experimental acidification has been used as a means of determining the effects of acid deposition. It has been performed by different methods, for example, by application of sulphuric acid, elementary sulphur and ammonium sulphate (Tamm and Popović, 1995). Most studies indicate that experimental acidification reduces carbon (C) mineralisation (Bryant et al., 1979; Klein et al., 1984), while net N mineralisation is sometimes reported to decrease (Francis, 1982; Klein et al., 1984) and sometimes to increase (Tamm et al., 1977; Persson et al., 1989).

The recovery of ground vegetation following clear-cutting is characterised by increased levels of light and nutrients, which favour colonisation by fast-growing grasses and forbs rather than dwarf shrubs. The N sink capacity of the ground vegetation following disturbance rapidly changes over time and depends on the recruitment of the pioneer flora. Wavy hair-grass (*Deschampsia flexuosa* (L.) Trin.) is a strongly dominant component of the ground flora following clear-cutting in northern Europe. Unlike many other species established after clear-cutting, it has a poor soil seed bank and is initially recruited from rhizomes, but increases its cover from seeds produced in the second year and later after harvesting (Granström, 1986).

The aim of the present study was to examine how different pre-harvest treatments, namely N fertilisation, soil alkalinisation by liming and soil acidification by sulphur powder, influence the N dynamics following clear-cutting and harvesting of a Norway spruce (*Picea abies* (L.) Karst.) forest. Nitrogen budgets were prepared through quantitative estimates of sources and sinks of inorganic N in the soil, net N mineralisation rate, leaching losses and ground vegetation uptake during the first four years following clear-felling of an experimental forest stand at Farabol in southern Sweden. Literature data were then used to calculate whether immobilisation of N in stumps and dead roots could contribute to the N budget.

The hypotheses were: (1) inorganic N sources (deposition, net N mineralisation) are balanced by the main N sinks (N uptake in ground vegetation, N leaching and accumulation of inorganic N); (2) liming increases nitrate-to-ammonium proportions in all internal fluxes, leading to increased N leaching; (3) acidification by sulphur hampers nitrification, leading to reduced N leaching; (4) N fertilisation increases the amplitude of N turnover; and (5) N uptake by ground vegetation and N leaching are negatively correlated.

2. Materials and methods

2.1. Site description

The experimental site, 131 Farabol, is situated in southern Sweden. Main site characteristics are shown in Table 1. The bedrock is granite or gneiss–granite, covered with a sandy loam glacial till. The dominant tree component before clear-cutting was a mature stand of Norway spruce. The ground vegetation before clear-cutting was dominated by forest mosses with a small number of *D. flexuosa* plants (Hallbäcken and Zhang, 1998).

2.2. Experimental design

The Farabol experiment was started in 1976. The initial objective was to determine the effects of accelerated soil acidification, N fertilisation and lime addition on soil and tree stands. The experiment consisted of four treatments (control, liming, S acidification and N fertilisation) in a randomised block design with three blocks. Sulphur (S) powder was used instead of sulphuric acid to reduce possible acute effects of the acid treatment. $CaCO_3$ and S additions were given in small annual doses over 12 years to avoid possible shock effects, and the N fertiliser was applied every fourth year as 200 kg urea-N ha^{-1} (Table 2). The 12 plots studied each measured 30 m × 30 m. The experimental area was clear-cut in early March 1992 according to the whole-tree harvesting concept, i.e., felling residues including tops and branches were carefully removed from the plots in addition to the stems. The site was replanted with 4-year-old seedlings of Norway spruce in May 1992. Supplementary plantings were made in September 1992 and May 1994. Two 30 m × 30 m forested reference plots (00) were established in a nearby spruce forest in 1992 with the aim of comparing the dynamics of inorganic N in intact forested plots and in the clear-cut. One of the reference plots (block 2) was destroyed by a storm in 1993 after which only one reference plot could be used.

2.3. Nitrogen deposition

Nitrogen deposition before clear-cutting was determined monthly during 1990 and 1991 as open field deposition near block 1 and 3, with three collectors per site. The water samples were stored in a freezer (−18 °C) and the samples from each occasion and site were pooled by weighted volume prior to chemical analysis. The open field deposition in 1990 and 1991 was compared with that at two nearby locations (Hjärtsmåla and Dalanshult, Swedish Environmental Research Institute), and the relationship obtained was used to estimate open field deposition at Farabol in 1992–1995. Because the ground vegetation on the clear-cut had low leaf area index, the capture of N by the ground vegetation was considered to be insignificant. Therefore, open field deposition was used to estimate N deposition to the clear-cut area.

2.4. Soil sampling

Two major soil samplings for quantitative determinations were made after clear-cutting, on 1 October 1992 and on 24 October 1994, i.e., 7 and 31 months after clear-cutting, respectively. The samples were collected from the 0, Ca, S, U and 00 plots and were taken from the litter (L) layer (O_i horizon), humus (FH) layer (O_{e+a} horizon) and the 0–10, 10–20 and 20–30 cm mineral soil layers in five soil profiles within each of the plots. The L and FH samples were taken with a 250 cm^2 circular frame and the mineral soil samples were taken with a 4.5 cm diameter steel corer. Samples from the same soil layer and plot were pooled to form a composite sample.

In addition to the two quantitative samplings, soil cores ($n = 5$ per plot) for monitoring pH (H_2O) and concentrations of KCl-extractable ammonium and nitrate were taken to a depth of 30 cm in the mineral soil in the 0, Ca, S, U and 00 plots during spring, summer and autumn 1990–1996. These concentrations were combined with the soil pool estimates made during the major samplings to estimate the dynamics of ammonium and nitrate before and after clear-cutting.

2.5. Ground vegetation

Above-ground biomass was sampled in each experimental clear-cut plot at the time of peak biomass (July–August) and at the time of early spring (April–May) each year except for the first