A single incident of soil P leaching in a mature forest corresponds to 10 years of average leaching

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Abstract

Incidental P losses from non-point sources may contribute to eutrophication and to decreased soil fertility. These incidents have been related to heavy rainfall on freshly fertilized agricultural soils and little is known about such incidents on more natural soils or in forests. The aim of this work is to determine if incidents of high P leaching also occur in spruce forests, and if such incidents are of significance in P cycling. We found a peak in the mineral soil solution showing that single events of high P leaching occur. The orthophosphate concentration in the Bf-horizon of the 80-year old spruce forest peaked in the autumn of the second year of a continuous monitoring. The concentration increased by more than 85 times compared to the highest concentration obtained earlier during the sampling. The amount leached during this 6 months peak is 10 times higher than the average annual leaching. This P leaching might be due to a combination of high P deposition/through-fall and a high anion exchange with dissolved-organic-carbon and Cl^-. We suggest that single events of high sub-surface P leaching may contribute to the overall P leaching, and might increase with the global warming as more DOC is expected to be released to the soil solution.

Key words: Anion exchange, DOC, Dissolved phosphorus, Forest soil, Lysimeters, P transport,

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1. Introduction

P leaching from diffuse sources such as soil is an increasing problem. Every soil has a sorption maximum, above which P is can no longer be held by the soil. This saturation level has been reached in some agricultural soils, resulting in extensive P leaching. P leaching from soil is becoming an increasing problem and is causing eutrophication of surface waters throughout the world. P leaching has been considered to occur mainly from surface runoff and soil erosion (Sharpley, 1995; Pote *et al.*, 1996). Leaching of P through the soil profile has been shown to occur mainly in macro-pores in agricultural soils (Wildenschild *et al.*, 1994). P also accumulates in forest soils as a result of repeated fertilization (Saggar *et al.*, 1998; Fransson and Bergkvist, 2000). Forest fertilization is, however, not common practice, and the contribution from forests to eutrophication has been considered negligible compared to the contribution from agriculture (Haygarth and Jarvis, 1999). The extent of forest fertilization might increase in the future due to the increasing demand for renewable energy. Leaching events occurring in forests might, however, teach us more about what happens on other soils as well. Most reports indicate that P leaching is usually the organic form passing down through the soil profile (Fransson and Bergkvist, 2000). Models describing P leaching predict changes in soil P test values and P leaching (Schoumans and Groenendijk, 2000), but do not consider any contribution from extreme events**.** There are, however, indications that leaching from forest soils is not uniform over the year. For example, 61% of the P leaching from the floor of a mature *Pinus radiata* stand occurred within two months (Cortina *et al.*, 1995). However, little P is supposed to leach from the deeper horizons due to the efficient chemical sink found at these soil depths (van Riemsdijk and van der Linden, 1984; Borggard *et al.*, 1990; Freese *et al.*, 1992). NO_3 is the major N compound that leaches from the soil, and the amount leaching is regarded as being governed by the C/N ratio in the soil (MacDonald *et al.*, 2002). The nitrification in soils is a biological process and the geochemical contribution has been considered negligible.

2. Materials and methods

2.1 Site description

The forest is located in southern Sweden, close to Brönnestad (56°05'N, 13°39' E; alt. 105 m above sea level). Mean annual precipitation of this area is 750 mm, mean temperature is 16 °C during the warmest month, and -2 °C during the coldest. The site is a homogeneous, well-drained, Haplic podzol (Anon, 1988). It has developed on a sandy-silty, glacial, non-calcareous till. There are no altitudinal differences and the soil is free from solid rocks down to several

meters. The forest stand consists of first generation Norway spruce (Picea abies L. Karst), planted about 80 years ago, when the site was extensively grazed. The canopy is closed and the ground cover is dominated by Deschampsia flexuosa (L.) Trin.

2.2 Treatments

The site was used for a fertilizer study when the samples were collected (Fransson *et al.*, 1999). The first treatment was initiated on 30 November 1994. Plots sized 15x15 m, and distributed in three blocks according to a randomized block design, were treated with easily soluble superphosphate (P20, Supra/Hydro) and KCl (refined and crushed, Supra/Hydro), slowly soluble sedimentary phosphorus (North African, Khouribia) and biotite (Supra/Hydro), or slightly hardened wood-ash (CFB-ash, Perstorp). Additional plots were treated with one of the above materials plus crushed dolomite lime (Steetley Maglime Supermix, 0-2mm). Plots that were limed only and untreated plots were used as controls. Data on elemental concentrations in control soil and treated soils have been presented by Fransson *et al.* (1999). No correlation was found between the treatment and the B-horizon soil chemistry; therefore, no results regarding the treatments are presented in this paper.

2.3 Sampling and analyses

Percolation water was collected from the soil using vacuum lysimeters at 17 different times over a two year period. Two tension lysimeters (prenart-quarts, 50 kPa) known to be inert with respect to phosphorus were placed in the B-horizon at 40 cm depth in each plot. The lysiometers were installed in the summer of 1994 and left to equilibrate for two months. Sampling of percolation water started in September 1994 and continued until November 25th 1996. On each sampling occasion, water was collected for two weeks in glass bottles that were kept below ground in plastic containers so they would remain cool and not be exposed to light. At each sampling up to 50 samples were analyzed, but most times very little water was recovered from a few of the lysimeters and the two samples from that plot was merged. This reduced the number of samples from each sampling to between 24 and 45 samples Through-fall and open-field solution was collected using one funnel in each plot. Phosphate concentration in the solution was determined using the molybdate-blue method (Murphy and Riley, 1962), and ammonium concentration was analyzed according to the method of Ruzika and Hansen (1981). Dissolved organic carbon was determined on an aliquot of the sample using a total organic carbon analyser (TOC-500, Shimadzu). The residue was frozen in the laboratory. Cl^- and NO_3^- concentrations were determined using anion chromatography (Dionex IonPac, AS14A).
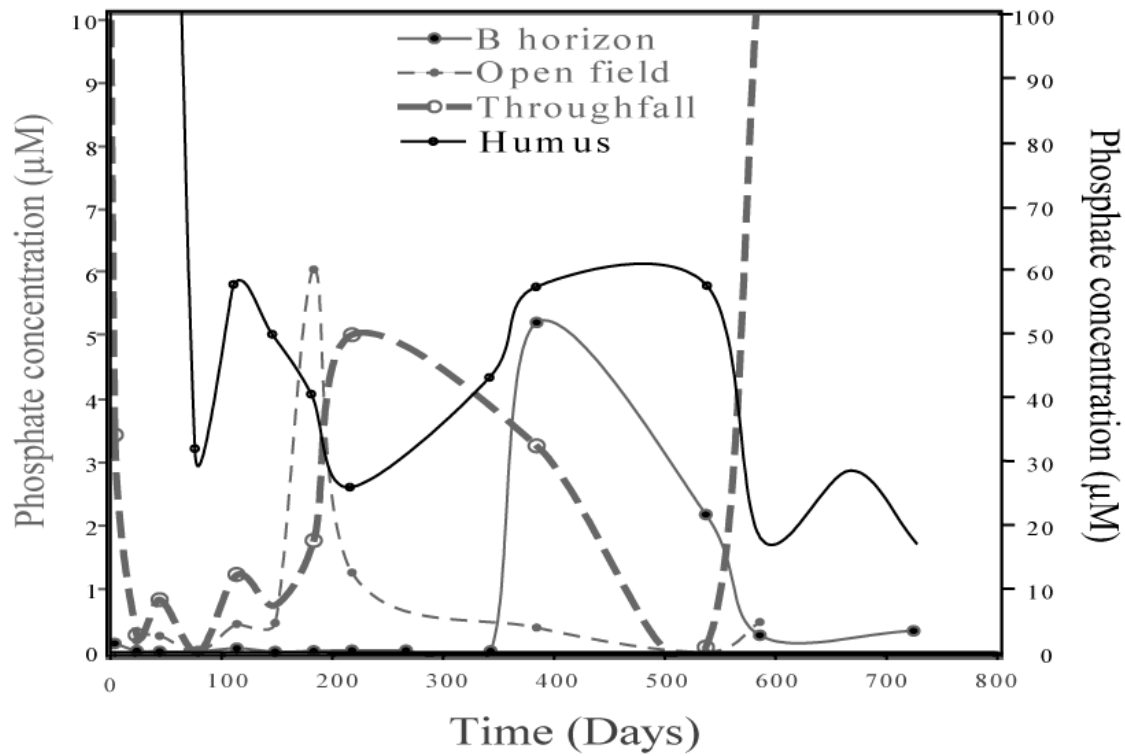
Incidents may correspond to 10 years of P leaching

Figure 1: The $H_2PO_4^-$ concentration in the soil solution reaching the soil surface (open field and through-fall), leaching from the B-horizon (gray lines), and leaching from the humus (black line) of a spruce forest soil over a two year period. Left axis is the B-horizon, open-field and through-fall P concentrations; right axis is Humus P concentration.

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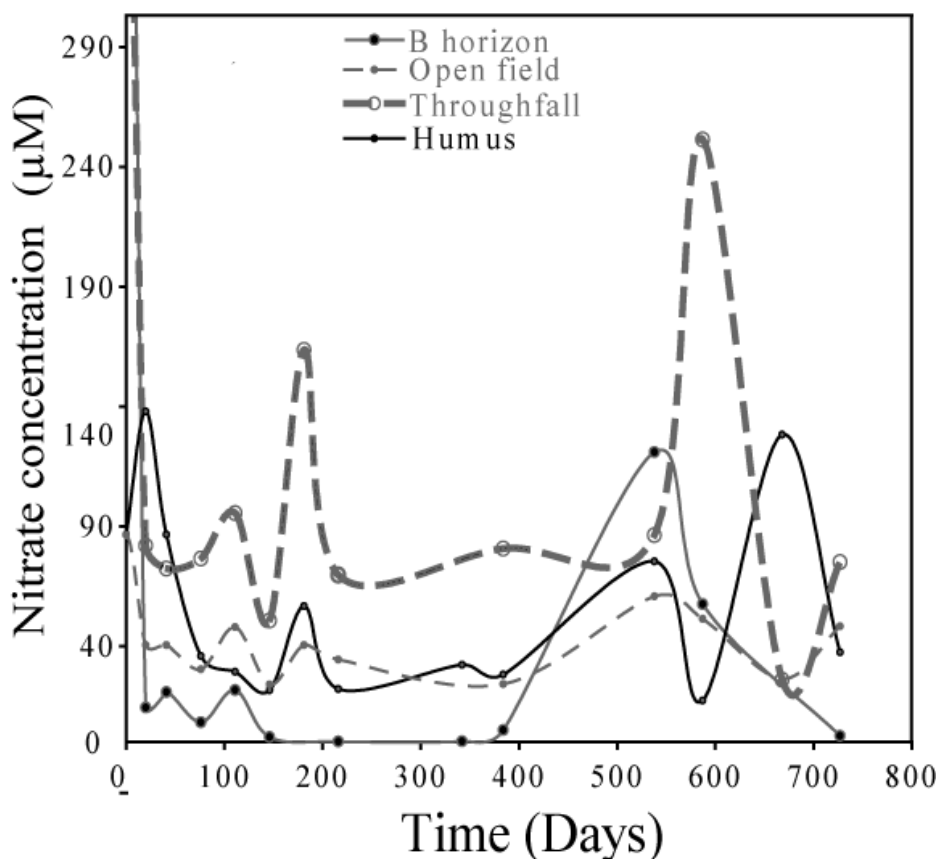Incidents may correspond to 10 years of P leaching

Figure 2: The NO_3^- concentration in the soil solution reaching the soil surface (open field and trough-fall) leaching from the B-horizon (gray lines), and in the humus (black line) of a spruce forest soil over a two year period.

3. Results

At one single event the P concentration in soil solution of the B-horizon increased by more than 85 times compared to the background concentration, and more than 170 times compared to the average level (Fig 1). There treatment had no effect on the P levels in the B-horizon; the peak was detected in the controls plots as well as in the treated plots. The NO_3^- concentration in the soil solution was 60 times higher than the average level obtained from the B-horizon during the sampling (Fig 2). An increase soil solution Cl^- concentration (Fig 3) preceded, and an increase in NO_3^- followed, the P peak in the B-horizon.

This sudden peak in P concentration decreased slowly during the final part of the study, but never reached the low concentrations determined prior to the peak. The NO_3^- concentration, however, returned to background levels. The peaks were detected in random lysiometers and

showed no relationship to the management of the forest. The P could be followed through the soil as the peak moved from the deposition, open field and through-fall, (Fig 1). No such retention could be observed for NO_3^- were the peak was detectable in the soil profiles at approximately the same time and seemed to be initiated by a high NH_4^+ concentration (Fig 4). At approximately the same time as the NH_4^+ peak a peak in dissolved-organic-carbon was found in the soil solution of the B-horizon (Fig 4). The amount leaching from the Bf-horizon is 1.09 kg ha-1 P over the period tested (table 1).
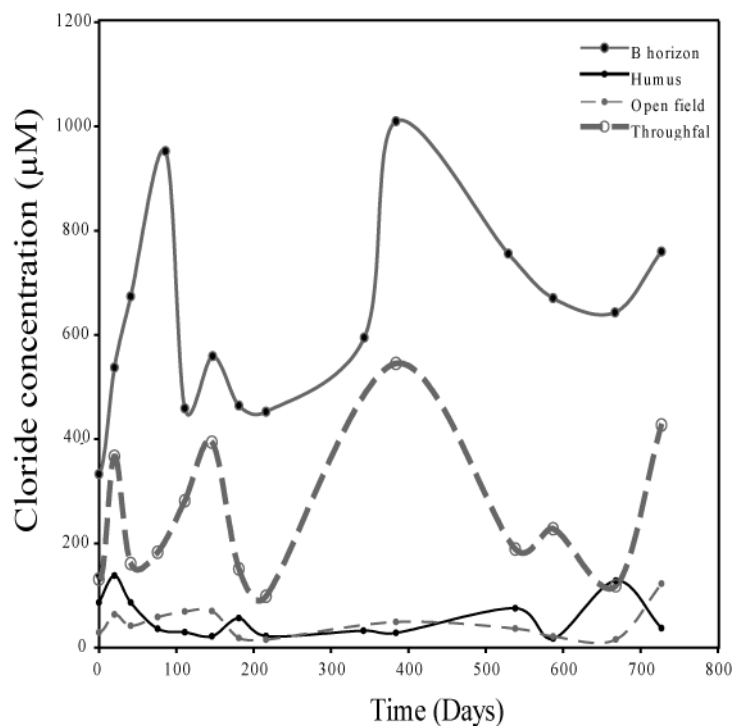
Figure 3: The Cl⁻ concentration in the soil solution reaching the soil surface (open field and trough-fall), leaching from the B-horizon (gray lines), and in the humus (black line) of a spruce forest soil over a two year period.
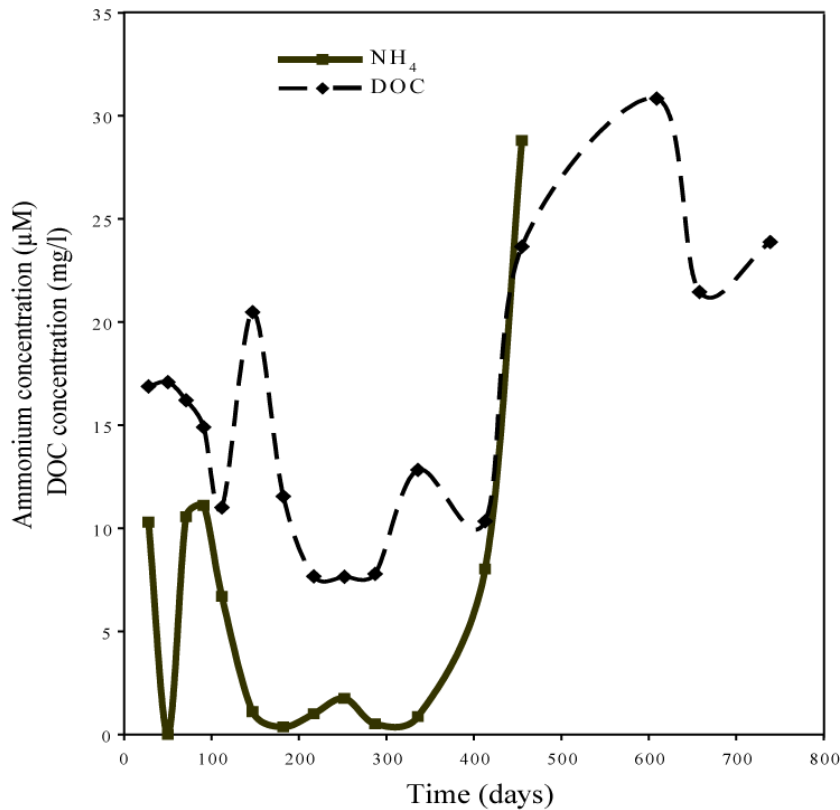

Figure 4: NH$_4^+$ and DOC concentrations in the soil solution of a forest soil over a two year period.

Table 1: Phosphorus flow to the soil and the P flow from different soil horizons during two years of monitoring of a mature Swedish spruce forest.

Fraction	P (kg/ha)
Open field	0.55
Through-fall	3.59
Humus	30.53
B-horizon	1.09

4. Discussion

The transport of inorganic P through the soil profile revealed by the shifting of the high P concentration peak was unexpected, and showed that under favorable circumstances P may be transported without being adsorbed. Incidents of P transport through the profile have been

reported from agricultural soil, but always in connection with fertilization and heavy rain-fall (Preedy *et al.*, 2001; Withers *et al.*, 2003). No P transport was detected from the B-horizon in a forested podsol in Finland – no P transport was detected below the P horizon – even though the forest was clear cut and the P transport from the O horizon increased (Piirainen *et al.*, 2004). In a long-term study of P availability two of the factors explaining most of the variation were increasing DOC and sulfate in the through-fall (Tahovská, et al. 2018). This is consistent with our results and anion exchange may be the mechanism responsible. There were no incidents of high P leaching reported from this study. The anion resin bags in the study of Thaovska et al. (2018) accumulated P during 6 month periods and the resolution was low and would not detect incidents of incidental P leaching.

During this event 10 times more P was leached during 6 month than the average annual leaching. The amount of P that leached from the different horizons has been estimated by calculating the areas beneath the different curves (Fig 1). The water volume leached from each horizon was calculated as a fraction of the through-fall. The fraction of the through-fall leaching form each horizon was calculated from data collected from two similar forests in the same area (Bergkvist and Folkesson, 1995). Earlier measurements have shown a P deposition of 0.23 kg P ha^{-1} year^{-1} (Westling and Hultberg, 1990), which is comparable to our calculations that show a deposition of 0.28 kg P ha^{-1} year^{-1}. Because the amount in the through-fall is higher than in the open-field data, the trees seem to be efficient in filtering the air for phosphate.

The total export from forested areas in Finland was calculated to be on average 0.09 kg ha-1 year-1 (Vuorenmaa *et al.*, 2002). The leaching from this study is more than five times higher than expected. Results from the Hubbard Brook area showed a leaching of 0.07 kg ha-1 year-1 from forested soil, the concentration, however, increased due to clear cutting to 0.7 kg P ha-1 year-1 (Yanai, 1998). The amount determined at the Hubbard Brook area after the clear-cut could be compared to the amounts found in our study. This indicates that a process involving organic matter mineralization is involved.

The amount of P reaching the B-horizon is about 1/3 of the amount in the through-fall. This P is leached during only 6 of the 25 months that the experiment lasted. Prior to the P peak a massive Cl- peak could be detected in the B-horizon (Fig 4), and we suggest that the combination of a high P concentration in the soil and a high DOC and Cl$^-$ transport combined to produce the favorable circumstances responsible for the leaching observed in the present

study. Low-molecular DOC is known to reduce the P leaching in soil due to anion exchange (Earl *et al.*, 1979; Evans, 1985; Comerford and Dyck, 1988).

5. Conclusion

We conclude that this transport of P may contribute to the total P leaching, and, perhaps more importantly, to the P being removed from the rhizosphere and leached to deeper levels where it is less available for the trees. However, we have shown that the uptake of P by oaks is not limited to the superficial soil layers (Göransson *et al.*, 2006; Göransson *et al.*, 2007). The importance and consequences of this downward transport for P uptake by trees needs further investigation. In order to accurately predict the total P leaching from soil the contribution from these kind of single events needs to be evaluated. Increasing global warming, and the resulting increase in organic matter mineralization in temperate areas, might have a significant effect on P cycling and especially on P leaching.

6. Acknowledgements

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7. References

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