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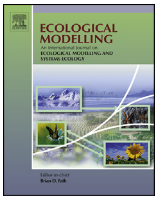

Storm disturbances in a Swedish forest—A case study comparing monitoring and modelling

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ABSTRACT

A Norway spruce (*Picea abies* Karst) forest site in southwest Sweden was chosen to study the effects of storm disturbances over the period 1997–2009, during which two storms, 'Lothar' (December 1999) and 'Gudrun' (January 2005), affected the area. Monitored deposition data, soil water chemistry data and forest inventory data were compared with the predictions of an integrated ecosystem model, ForSAFE, in an effort to reveal and understand the effects of storms on acidification/recovery in forest soils. Both storms caused windthrow loss leading to increased nitrate and sulphate concentrations in soil water as a result of stimulated mineralization. *Lothar* led to increased concentrations of Na^+, Mg^{2+}, and Cl^- in soil water due to sea-salt episode. No general sea-salt episode was seen following *Gudrun*, but small sea-salt episodes were observed in 2007 and 2008. Each sea-salt episode caused a temporary decrease of pH, and a subsequent recovery, but overall, the soil water pH decreased from 4.54 to 3.86 after *Lothar*. Modelling suggested that the site was recovering from acidification from 1990s, and would continue to recover in future. Both modelled and monitored data showed that storm caused disturbances in the recovery; monitored data even suggested that soil acidification happened due to storm disturbances. Sea-salt episode does not increase soil acidity in the long term, and will probably decrease the soil acidity by replenishing the base saturation. The modelled data also suggested that storms with only windthrow would not have effects on soil acidification recovery in the long term, but they may influence the soil fertility by losses of base cations.

1. Introduction

Swedish forests generally grow on nutrient-poor soils, mainly tills from nutrient-poor bedrocks such as granites and gneisses (Wastenson et al., 1990). The fertility of these soils has been further affected by acid deposition (Reuss and Johnson, 1986). Furthermore, whole-tree harvesting has become more common in recent decades, leading to further removal of base cations (Iwald et al., 2013; Akselsson et al., 2007; Brandtberg and Olsson, 2012). One main effect of acid deposition (S and N) on forest soils is the increased leaching of sulphate and nitrate coupled with nutrient cations such as Mg^{2+}, Ca^{2+} and K^+ causing base cations (BC: Ca^{2+}, Mg^{2+}, K^+) depletion from the soil (Reuss and Johnson, 1986). Base cations depletion in forest soils due to high acid deposition has been simulated in several model approaches in regional scale (Sverdrup and Rosen, 1998; Akselsson et al., 2007) and in catchment scale (Navrátil et al., 2007; HruŠka et al., 2012; Oulehle et al., 2007). However, the N deposition in most of Sweden is generally low (Simpson et al., 2011), and northern forest ecosystems are normally nitrogen (N) limited (Tamm, 1991; Jonard et al., 2015). Thus, leaching of inorganic nitrogen is generally very low in Swedish forests, except for the southwesternmost part with the highest present and historical N deposition, where the nitrate concentration in soil water is often elevated (Akselsson et al., 2010).

S deposition to forest ecosystems has strongly decreased since the 1990s throughout Sweden, but recovery from acidification has been reported to be very slow (Pihl Karlsson et al., 2011; Akselsson et al., 2013). This has also been demonstrated through dynamic modelling (Sverdrup et al., 2005), and can be explained by the slow replacement, through weathering and deposition, of the base

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cations that were lost during acidification. Although N deposition has decreased in some areas of Sweden, it has generally remained constant (Pihl Karlsson et al., 2011). N accumulation in forest soils due to high loads of N deposition is also preoccupying for soil acidification recovery. In forest soils with high N content, intense N leaching episodes may occur following ecosystem disturbances such as clear-cutting (Gundersen et al., 2006; Zanchi et al., 2014), or windthrow from storms (Legout et al., 1999). Intense N leaching episodes, for which no causal explanation was found, have also been reported (Van der Heijden et al., 2011). The consequences of such episodes are increased acidity and increased aluminium concentrations in soil solution, along with increased leaching of base cations and aluminium (e.g. Lundell et al., 2001). In the long term, N leaching although episodic may strongly impact the recovery from soil acidification.

Natural ecosystem disturbances, such as storms, droughts and fire, may also have considerable effects on the physical, chemical and biological properties of the soil, and thus the soil fertility. Storms are one of the most common types of ecosystem disturbances in Swedish forests (Schlyter et al., 2006). Storms are high-wind episodes, sometimes accompanied by heavy rain, which may lead to a reduction in canopy closure due to windthrow and stem breakage, thereby also increasing solar radiation levels in stands (Vodde et al., 2011). Storms may also lead to an increase in the availability of nutrients and water (Vygodskaya et al., 2002; Legout et al., 1999), as a result of the reduced uptake and the increase in woody debris which will decompose and release nutrients (Vodde et al., 2011). In fact, the stimulation of mineralization of organic matter, particularly the rate of nitrification, has been reported to be an important change resulting from ecosystem disturbances (Attiwill and Adams, 1993; Dahlgren and Driscoll, 1994; Legout et al., 1999). This is often accompanied by the leaching of nitrate and BC (Dahlgren and Driscoll, 1994).

Apart from the effect of wind on trees, storms with high precipitation often cause sea-salt episodes. Sea-salt episodes affect the cation exchange in soil; and is known as the ‘sea-salt effect’ (Hindar et al., 1995). The cations transported by sea-salt episodes, primarily Na^+ and Mg^{2+}, cause the displacement of absorbed acid ions: hydrogen (H^+), labile aluminium (Al^{3+}) (Wright et al., 1988; Evans et al., 2001), and other BC: Ca^{2+} and K^+ (Hindar et al., 1994; Hindar et al., 1995). The relationship between soil acidity and the leaching of H^+, Al^{3+} and base cations is complex, but it is often observed that the pH falls and Al^{3+} increases and sea salt ions (Na^+, Mg^{2+}, and Cl^-) increase shortly after sea-salt episodes (Hindar et al., 1995; Pedersen and Bille-Hansen, 1995). Disturbances in acidification recovery as a result of sea-salt episodes have been observed in European and Swedish forests (Wright, 2008; Akselsson et al., 2013; Laudon, 2008). Wright observed that sea-salt episodes were responsible for more than one-third of the low ANC ($ANC < -50\ \mu eq\ l^{-1}$) episodes, which were considered as strong indicator of acid episodes, at Birkenes in Norway during the period 1975–2004. Akselsson et al. (2013) and Laudon (2008) pointed out that recovery from acidification was slow at some coastal forest sites in Sweden, as these sites are susceptible to sea-salt episodes.

The aim of this study was to investigate the effects of storms on the acidification/recovery processes in forest soils. We hypothesized that: the high deposition of sea salt and increased rate of nutrient mineralization caused by storms slow down the recovery trend of forest soils from past acidification. For this purpose, a site in southwest Sweden that suffered the effects of the storms ‘Lothar’ and ‘Gudrun’ was studied. ForSAFE, a numerical model simulating biogeochemical cycling in forest ecosystems, was applied with monitoring data from the site. Both monitoring data and modelled data were used to study the acidification/recovery trends and the influence of the storms ‘Lothar’ and ‘Gudrun’ on these trends. Finally, ForSAFE was used to simulate the influence of frequently occurring storms in the future on soil acidification recovery.

2. Materials and methods

2.1. Site description

The study site, was a 30 m × 30 m square plot located in a forest called Klintaskogen (55°62′ N, 13°44′ E) in the region of Scania (southwest Sweden), and is part of the Swedish Throughfall Monitoring Network (SWETHRO) (Pihl Karlsson et al., 2011). It is also one of 223 intensive monitoring plots managed by the Swedish Forest Agency. The average annual precipitation at Klintaskogen is 780 mm and the average annual temperature is 7.2 °C (average over 1961–2010). The site is about 25 km from the west coast and about 30 km from the south coast of Sweden. The elevation of Klintaskogen is about 105 m, and it is on the southwestern slope of the horst Romeleåsen.

Klintaskogen is a managed Norway spruce (*Picea abies* Karst) forest that was planted on a juniperous grass-land in the 19th century. The latest final felling occurred in 1957, and the site was replanted with Norway spruce. Klintaskogen suffered from the severe wind storm *Lothar* in December 1999, which caused windthrow of about 15% of the trees in the study plot. Another wind storm, *Gudrun*, also caused damage at the study site in January 2005, but tree loss (about 5% of the trees) was less severe.

The forest floor has a thin organic layer (3.5 cm) with 48% organic matter content (Loss on Ignition, LOI) (Table 1). The soil type is dystric regosol. The top 50 cm of the mineral soil profile is sandy and acidic with very low base saturation, and the exchange sites are mainly occupied by Al^{3+} (Table 1). The organic matter content decreases downwards from 10.8% to 2.3%, and the pH_{H_2O} increases downwards from 4.2 to 5.0, within the top 50 cm of soil (Table 1).

2.2. Monitoring data

The following parameters are monitored at the Klintaskogen site:

(a) **Deposition:** Thoughfall was collected monthly between 1997 and 2009 with a total of ten throughfall collectors along two sides of the study plot. Bulk rainfall was collected monthly in an open-field collector between 1997 and 2001.

(b) **Soil solution chemistry:** Soil solution was collected at 50 cm depth using tension cup lysimeters (5 replicates), three times per year from 1997 to 2009. The 5 sample obtained were combined into a composite sample on each sampling occasion for the analysis of: sulphate ($SO_4{}^{2+}$), Cl^-, nitrate ($NO_3{}^-$), ammonium ($NH_4{}^+$), Ca^{2+}, Mg^{2+}, Na^+, K^+, Mn^{2+}, Fe^{3+}, inorganic Al (iAl), organic Al (oAl) and dissolved organic carbon (DOC). Composite samples with volumes <50 ml were not analyzed. The ANC was computed as follows:

$$ANC = [Ca^{2+}] + [Mg^{2+}] + [K^+] + [Na^+] + [NH_4{}^+] - [SO_4{}^{2-}] - [Cl^-] - [NO_3{}^-] \quad (1)$$

where the concentrations are in the units $eq\ l^{-1}$.

(c) Forest inventories: Inventories were carried out on three occasions (1996, 1999 and 2004) within the intensive monitoring program led by the Swedish Forest Agency, and these inventories were complemented with an inventory in 2010, using the same methodology. On each occasion, the diameter at breast height of each tree was measured, and the tree and crown heights were measured in a selected aliquot representing 20% of the trees in the plot.