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Tree species is the major factor explaining C:N ratios in European forest soils

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ABSTRACT

The C:N ratio is considered as an indicator of nitrate leaching in response to high atmospheric nitrogen (N) deposition. However, the C:N ratio is influenced by a multitude of other site-related factors. This study aimed to unravel the factors determining C:N ratios of forest floor, mineral soil and peat top soils in more than 4000 plots of the ICP Forests large-scale monitoring network. The first objective was to quantify forest floor, mineral and peat soil C:N ratios across European forests. Secondly we determined the main factors explaining this C:N ratio using a boosted regression tree analysis (BRT), including fifteen site and environmental variables.

Ninety-five percent of the C:N ratios were between 16 and 44 in the forest floor, between 13 and 44 in the peat topsoil and between 10 and 32 in the mineral topsoil. Within the aerated forest floor and the mineral soil, the C:N ratios decreased with depth, while in the hydromorphic forest floor and the peats no clear trend with depth was observed.

Tree species was clearly the most important explanatory variable for the C:N ratio in both forest floors and topsoils, while it was soil type in the deeper mineral soil layers. The lowest C:N ratios both in the forest floor and the top mineral soil were found in black locust (*Robinia pseudoacacia* L.) and black alder (*Alnus glutinosa* L.) stands, both N fixing tree species. While in the forest floor the highest C:N ratios were found in evergreen species like pine, cork oak (*Quercus suber* L.) and eucalyptus, the pine species and Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) showed the highest C:N ratios in the mineral soil. The second most important explanatory variable in the forest floor and mineral topsoil was the biogeographical zoning (ecoregion). In the peat topsoil and in the deeper mineral soil layers it was the humus type. Deposition and climatic variables were of minor importance at the European scale.

Further analysis for eight main forest tree species individually, showed that the influence of environmental variables on C:N ratios was tree species dependent. For Aleppo pine (*Pinus halepensis* Miller) and holm oak (*Quercus ilex* L.), both with a typical Mediterranean distribution, the relationship between N and S deposition and C:N ratio appeared to be positive. This study suggests that applying C:N ratios as a general indicator of the N status in forests at the European level, without explicitly accounting for tree species, is too simplistic and may result in misleading conclusions.

1. Introduction

Most temperate forest ecosystems that are prone to excessive nitrogen (N) deposition have traditionally been considered N limited, i.e. fertilizer experiments showed tree growth response only to added N (Aber et al., 1989). Elevated N deposition represents a continuous source of plant-available N in surplus to plant-available N resulting from organic matter mineralisation and/or N_2 fixation. When N loading reaches a level at which inputs to the forest ecosystem are in excess of both biological uptake and the storage capacity of the soil, then nitrate will leach below the rooting zone, a state termed N saturation (Aber et al., 1989). Forest floor C:N ratios have been proposed as indicators for nitrate leaching mainly in coniferous forest ecosystems (Dise et al., 1998a; Emmett et al., 1998; Gundersen et al., 1998; Macdonald et al., 2002). In deciduous forests with thin forest floors, the C:N ratio of the mineral topsoil was shown to be a better indicator of the N status than the forest floor C:N ratio (Vesterdal et al., 2008; Gundersen et al., 2009). Along the same lines, Kristensen et al. (2004) found that in broadleaved forests topsoil pH and throughfall N correlated better with soil solution nitrate concentrations than forest floor C:N ratio.

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However, in North America, Lovett et al. (2002) reported a negative relationship between forest floor C:N ratio and nitrate leaching in deciduous stands. Their analysis indeed demonstrated that the C:N ratio in the catchments soils was mainly determined by tree species composition. Also in other studies, nitrate leaching was not solely and generally governed by forest floor C:N ratio. In Switzerland, Thimonier et al. (2010) reported that nitrate leaching occurred in forest stands subjected to N deposition levels >10 kg ha^{-1} $year^{-1}$ and where the C:N ratio in the forest floor was below a certain threshold. However, they concluded that there was no general threshold and that nitrate leaching depended rather on other soil variables such as the organic C stock and the humus type.

Low C:N ratios have additionally been associated with increased emission of N_2 and reactive N trace gases from soil (Sutton et al., 2011), especially from peat soils (Klemedtsson et al., 2005). Several studies have shown that N deposition and nitrous oxide (N_2O) as well as nitric oxide (NO) emissions from forest soils are positively correlated (Pilegaard et al., 2006; Skiba et al., 2006) – from 3.7% (under coniferous) to 5.7% (under broadleaves) of N deposited could be lost as N_2O (Denier van der Gon and Bleeker, 2005). Some studies have found that sites high in soil N concentrations and with low C:N ratios had a lower capacity for methane oxidation than those with low N concentrations and high C:N ratios (Wang and Ineson, 2003; Bodelier and Laanbroek, 2004; Reay and Nedwell, 2004; Saari et al., 2004). Further, in N saturated forest ecosystems, where N is not limiting microbial growth, additional N inputs could impede soil respiration and particularly the later stages of organic matter decomposition (Janssens et al., 2010).

The use of forest soil C:N ratios alone or in combination with throughfall N input as an indicator of nitrate leaching reflects that the C:N ratio does not suffice as a single proxy for high N status. Apart from N deposition, the C:N ratio is potentially influenced by a multitude of other site-related variables. Koerner et al. (1997) and Verheyen et al. (1999) found that former agricultural soils displayed a lower C:N ratio than soils in old forests. In sites under long-term forest cover, Goodale and Aber (2001) reported that historical logging and burning caused higher C:N ratios compared to old growth forests. In common garden experiments including common European broadleaf species and Norway spruce, forest floor and topsoil C:N ratios differed among tree species (Vesterdal and Raulund-Rasmussen, 1998; Vesterdal et al., 2008). Ollinger et al. (2002), Aitkenhead-Peterson et al. (2006) and Cross and Perakis (2011) showed a similar effect. Soil type has been reported to influence C:N ratios in Northern European studies, with lower C:N ratios in fine-textured than in coarse-textured mineral soils (Vejre et al., 2003; Callesen et al., 2007). The combined influence of tree species and soils on C:N ratios presents a challenge for interpretations of large N input–output monitoring datasets across Europe. For instance, Kristensen et al. (2004) suggested that broadleaved stands (with lower C:N ratios) leached more N than conifers at comparable N inputs, but concluded that the tree species effect was likely confounded with a soil type effect as broadleaved tree species are more frequently found on fine textured soils. As suggested by Gundersen et al. (2009), there is an obvious need to disentangle how factors that control nitrate leaching – or their indicators such as soil C:N ratio – are affected by tree species and soil type, respectively.

The aim of this study was to unravel the factors determining the C:N ratios of forest floor, mineral and peat topsoils in more than 4000 forest plots located on a systematic 16 × 16 km grid. The first objective was to quantify forest floor and mineral or peat topsoil C:N ratios across European forests. The second objective was to determine the main factors that explain the C:N ratios found in those forest soils.

2. Materials and methods

2.1. Network, survey, sampling and analytical methods

In 1985, the International Co-operative Programme on Assessment and Monitoring of Air Pollution Effects on Forests (ICP Forests) of the United Nations ECE Convention on Long-Range Transboundary Air Pollution (CLRTAP) set up a systematic 16 × 16 km grid (Level I) throughout Europe to annually assess the condition of the forest ecosystems. Under the Forest Focus Regulation (EC) No. 2152/2003, 22 European countries participated in a large-scale soil inventory (BioSoil) on 4928 forest stands in this Level I grid. The sampling and analyses were performed between 2006 and 2009. The data were stored in the Level I Forest Soil Condition Database (FSCDB.LI.2.1) of ICP Forests.

On each forest plot a detailed profile description was carried out and soils were classified according to the World Reference Base for Soil Resources (WRB; IUSS Working Group WRB, 2006, 2007). The physical and chemical status of the soil was assessed by sampling and analysis of composite forest floor and soil samples to a depth of 80 cm following the methods outlined in the ICP Forests Manual (FSCC, 2006).

The forest floor was sampled according to its sublayers: OL (litter layer), OF (fermentation layer) and OH (humified layer, or OF and OH combined in one sample) or in hydromorphic forest floors: Hf (fibric), Hfs (mesic) and Hs (sapric) (FSCC, 2006). Since it was not mandatory to sample the OL layer, C:N ratios in the OL layer could only be calculated for 1240 of out 4928 stands. Unless stated otherwise, the term 'forest floor' refers to the combined OF and OH layer. The mineral soil was sampled according to four predefined fixed depth layers: 0–10 cm, 10–20 cm, 20–40 cm and 40–80 cm where the 0 cm line corresponds to the boundary between the forest floor and the underlying mineral soil or peat layer. The topsoil is here defined as the 0–10 cm layer. In a number of countries, the 0–5 cm and the 5–10 cm depths were sampled separately. The composite soil samples consisted of at least five equal mass subsamples, except for situations with a variable lower depth limit. Organic C (OC) was measured by dry combustion method, mostly using a total C analyser (ISO, 1995a; Matejovic, 1993) and total N (TON) either by dry combustion (ISO, 1998) or by the modified Kjeldahl method (ISO, 1995b). Bi-annual interlaboratory comparisons showed that the analytical results for OC and TON were highly comparable between the laboratories (Cools et al., 2003, 2006, 2007; Cools and De Vos, 2009). In addition, in most stands undisturbed soil cores were taken for the measurement of the bulk density (ISO, 1993) at the same depth as the samples for chemical analysis and the percentage of coarse fragments was assessed (FSCC, 2006).

The C:N ratios were calculated in two ways. Firstly, based on the ratios between concentrations in each of the individual soil layers (OC/TON, both in g kg^{-1}). Secondly, in order to obtain one C:N ratio for the forest floor and one value for the topsoil, weighted averages were calculated from the forest floor sub layers (OF and OH) and from the 0–5 and 5–10 cm layers. These weighted averages were based on the total mass (or stocks) of C and N in the individual layers, taking bulk density and stone content into account. As the deeper mineral soil layers were all sampled according to the same depth limits, no weighing was necessary.

In 1995, ICP Forests conducted a large-scale foliage survey on a subset of approximately 1400 plots of the Level I grid (Stefan et al., 1997). Assuming a 50% concentration of carbon, bootstrapped mean C:N ratios for the most common tree species were calculated.

2.2. Statistical analyses

Basic statistics were calculated using the TIBCO Spotfire S+ 8.2 for Windows (2010). Bootstrapping was used to obtain confidence