Soil inorganic N leaching in edges of different forest types subject to high N deposition loads

Short title: N leaching in edges of different forest types

Karen WUYTS[1*], An DE SCHRIJVER[1], Jeroen STAELENS[1,2], Lotte VAN NEVEL[1], Sandy ADRIAENSSENS[1], Kris VERHEYEN[1]

[1] Laboratory of Forestry, Dpt. of Forest & Water Management, Ghent University. Geraardsbergsesteenweg 267, B-9090 Gontrode-Melle, Belgium

[2] Laboratory of Applied Physical Chemistry (ISOFYS), Dpt. of Applied Analytical and Physical Chemistry, Ghent University. Coupure Links 653, B-9000 Gent, Belgium

Corresponding author: K. Wuyts, Laboratory of Forestry, Dpt. of Forest and Water Management, Ghent University, Geraardsbergsesteenweg 267, B-9090 Gontrode-Melle, Belgium. Telephone: +32 9 264 90 25. Fax: +32 9 264 90 92. E-mail: Karen.Wuyts@UGent.be

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Abstract

We report on soil leaching of dissolved inorganic nitrogen (DIN) along transects across exposed edges of four coniferous and four deciduous forest stands. In a 64-m edge zone, DIN leaching below the main rooting zone was enhanced relative to the interior (at 128 m from the edge) by 21 and 14 kg N ha^{-1} y^{-1} in the coniferous and deciduous forest stands, respectively. However, the patterns of DIN leaching did not univocally reflect those of DIN throughfall deposition. DIN leaching in the first 20 m of the edges was lower than at 32-64 m from the edge (17 vs. 36 and 15 vs. 24 kg N ha^{-1} y^{-1} in the coniferous and deciduous forests, respectively). Nitrogen stocks in the mineral topsoil (0-30 cm) were, on average, 943 kg N ha^{-1} higher at the outer edges than in the interior, indicating that N retention in the soil is probably one of the processes involved in the relatively low DIN leaching in the outer edges. We suggest that a complex of edge effects on biogeochemical processes occurs at the forest edges as a result of the interaction between microclimate, tree dynamics (growth and litterfall), and atmospheric deposition of N and base cations.

Keywords

atmospheric deposition / nitrate leaching / forest edge / edge effects / forest type / C:N ratio / inorganic nitrogen

1. Introduction

In many landscapes around the world, human activities such as timber harvesting, agricultural expansion, and urbanization increase the extent of forest fragmentation, making the forest edge the prevailing feature of the landscape matrix (Riiters and others 2002; Harper and others 2005; Broadbent and others 2008). In forest edges, nitrogen (N) throughfall deposition is enhanced relative to the forest interior (see De Schrijver and others (2007a) for a review). In the interior of N saturated forests, high levels of N deposition are associated with increased levels of dissolved inorganic N (DIN; ammonium (NH_4^+) + nitrate (NO_3^-)) leaching to the groundwater, predominantly as NO_3^- (MacDonald and others 2002; Kristensen and others 2004; Vestgarden and others 2004; De Schrijver and others 2008). Hence, higher levels of DIN leaching in forest edges in comparison with the forest interior can be expected. Yet, both lower (Balsberg-Påhlsson and Bergkvist 1995; Kinniburgh and Trafford 1996; Spangenberg and Kölling 2004) and higher (Balsberg-Påhlsson and Bergkvist 1995; Spangenberg and Kölling 2004) NO_3^- concentrations in soil water and DIN leaching fluxes have been detected at edges than further down the edge.

The proximity of the edge affects a variety of abiotic and biotic variables. Microclimatic variables such as air and soil temperature, light availability, and soil moisture are altered (Matlack 1993; Chen and others 1995; Gehlhausen and others 2000; Marchand and Houle 2006; Heithecker and Halpern 2007) and throughfall deposition fluxes of sulphur and base cations such as K^+, Ca^{2+}, and Mg^{2+} are enhanced (Draaijers and others 1994; Spangenberg and Kölling 2004; Wuyts and others 2008a). Moreover, higher tree growth rates and leaf area indices are reported at edges in comparison with forest interiors (McDonald and Urban 2004; Bowering and others 2006; Sherich and others 2007), potentially resulting in higher levels of N sequestration in biomass at the edge due to higher tree biomass (Spangenberg and Kölling 2004).

Our research objective was to investigate (i) whether DIN leaching in the soil is influenced by edge effects in both deciduous and coniferous forest types, and (ii) how this pattern of DIN leaching in edges relates to patterns of DIN throughfall deposition, of forest floor and mineral soil characteristics, and of N stored in stem biomass. In addition, we examined the effect of forest type on DIN leaching. We presume that the higher input of N deposition is expressed in enhanced DIN leaching near edges, and that this pattern of DIN leaching differs between forest types, since deciduous forest types are subject to smaller edge effects on DIN deposition than coniferous ones are (Spangenberg and Kölling 2004; Wuyts and others 2008a, 2008b).

2. Materials and methods

2.1. Site description

In two regions, located in Flanders (the northern part of Belgium) and approximately 135 km apart, eight homogeneous forest stands were considered (Fig. 1): two naturally regenerated stands dominated by silver birch (*Betula pendula* Roth; stands Bp1 and Bp2) and six planted monocultures of (i) pedunculate oak (*Quercus robur* L.; stands Qr1 and Qr2), (ii) Austrian pine (*P. nigra* ssp. *nigra* Arnold; stand Pn1) or Corsican pine (*Pinus nigra* ssp. *laricio* Maire; stand Pn2), and (iii) Scots pine (*Pinus sylvestris* L.; stands Ps1 and Ps2). The stands Bp1, Qr1, Pn1, and Ps1 were situated in the western part of Flanders and Bp2, Qr2, Pn2, and Ps2 in the northern part (Fig. 1). Site code, location, stand characteristics, and soil pH-KCl of the studied forest stands are presented in Table 1. Thinning in stand Ps2 about three years prior to the start of our measuring campaign caused DIN leaching to be locally and temporarily enhanced, higher than the input of N via throughfall deposition (von Wilpert and others 2000; Weis and others 2006). Hence, DIN leaching data from the Ps2 site was omitted from statistical analyses and figures.

All stands had an abrupt forest edge oriented towards the prevailing southwesterly winds. All forests were located on poor, well-drained soils of sand or loamy sand (Haplic podzols; FAO-ISRIC-ISSS 1998) with a low buffering capacity for acidifying deposition (Van Ranst and others 2002; De Schrijver and others 2006). During the entire sampling period, the groundwater table was deeper than 150 cm in all stands except Pn1 (> 120 cm) and Bp1 and Qr1 (> 80 cm). All forests were situated in areas with high density of intensive livestock farms. Analysis of the throughfall deposition data (Wuyts and others 2008b) showed that differences in edge effects between the two regions were less important than the differences between coniferous and deciduous forest stands. For the physical and chemical characterisation of the climate in the two regions, we refer to Wuyts and others (2008b). Historic maps from around 1775 and later showed that the sites were managed as heath, characterised by sheep grazing and turf cutting, until up to 80 years ago, and, from then onwards, were continuously covered by forest. The Qr1 stand was briefly managed as grassland around 1900. The edge of the Pn1 stand borders a busy highway at less than 5 m.

2.2. Experimental setup and sampling

In each stand, throughfall and soil solution were monitored year-round, soil samples were taken, and leaf area index (LAI) was determined at eight distance plots at 0, 2, 4, 8, 16, 32, 64, and 128 m from the edge, along a transect perpendicular to the forest edge. Throughfall water was collected using three collectors (funnels mounted on two-liter bottles) per distance plot (Wuyts and others 2008b). Soil solution was sampled at two depths, i.e., at 30 and 90 cm, by means of one suction cup lysimeter per depth and distance plot. Within one plot, the distance between the two lysimeters was at least 1 m. The lysimeters consisted of (i) a PVC pipe fitted with a porous ceramic cup (5 cm diameter, Eijkelkamp, The Netherlands) and inserted into the soil at an angle of 60° with the surface and (ii) an opaque, glass, one-liter bottle connected to the pipe via a polyethylene tube and stored belowground to keep samples cool. After each sampling, a pressure of -500 hPa was applied. Preferably, the lysimeters were installed where no understory vegetation occurred to avoid confounding influence of its N uptake. Brambles (*Rubus fruticosus* agg.) were carefully removed within a 3-m radius around the lysimeters in the first 20 m of Qr1, at the 64 m and 128 m distance plots of Pn1, and at the 16 m and 32 m distance plots of Ps1. The perennial herb *Holcus mollis* L. in the first 10 m from the edge of the Pn2 stand was not removed to avoid substantial disruption of the organic layer. The lysimeters were installed four months prior to the actual monitoring to check for proper performance, and were drained every two weeks to ensure close contact with the surrounding soil solution. The level of groundwater was monitored with piezometers; in the stands Qr1 and Bp1, soil solution was not sampled at 90 cm due to high ground water levels (> 80 cm deep). Soil solution and throughfall sampling took place fortnightly from 1 September 2005 to 30 August 2006. On each sampling occasion, sample volume in the throughfall collectors and the lysimeters was measured, throughfall samples were pooled volume-weighted per distance plot, and subsamples were taken to the lab. Aliquots of two consecutive sample collections were pooled volume-weighted into monthly samples for chemical analysis.

In February 2006, soil samples were taken with a 3.2 cm diameter soil auger from the fermentation and humus layer (together, FH) of the forest floor (i.e., the ectorganic layer) and from 0-5 cm, 5-10 cm, and 10-30 cm of the mineral soil. We took samples at three locations per distance plot and all samples were analysed separately. Next to this, the FH layer was collected in a 39 cm x 39 cm square at the outer edge (0-20 m from the edge front) and the forest interior (at 128 m from the edge). Density of the mineral soil was determined from the dry weight of undisturbed samples in cylinders of approximately 10^{-4} m^3.

In winter 2005-2006 and summer 2006, LAI was measured from digital hemispherical photographs (Nikon D70s with fish-eye lens Sigma EXDG Fisheye 8 mm 1:4 D) taken above each throughfall collector, using Gap Light Analyzer GLA 2.0 (http://www.ecostudies.org/gla). Stem volume was calculated from diameter at breast height and tree height measured for all trees within 10 m from the central transect axis in spring 2006, based on the equations by Jansen and others (1996).

In June 2008, leaves and current-year and older (> 1 year) needles were collected using telescopic secateurs at a fixed height of 12 m and from the shaded part of the crown. We sampled five trees located in the first 10 m of the forest edge and five trees in the forest interior. In the Qr1 stand, branches with leaves were too high to reach, while in the Ps1 stand, needles could not be collected due to safety reasons (next to a busy highway). Trees at the edges were sampled at the sheltered side opposite from the edge to avoid overestimation of the N concentrations by sampling sunlit leaves or needles. Dry weight and surface area of a leaf or needle subsample were measured to assess the specific leaf area (SLA, ratio of leaf area to leaf dry weight). Leaf surface areas were determined with the LI-3000 Portable Area Meter (LICOR); needle surface areas were estimated from needle length and diameter. Stem cores were taken from the same trees at 30 cm height above the root collar. Bark was excluded from chemical analysis and only fully intact stem cores, bored through the entire stem, were selected. Additionally, the length, diameter, and weight of the dry stem cores were determined to estimate wood density.

2.3. Chemical analyses

Subsequent to filtration (0.45 µm, Rothe), the monthly water samples were analyzed for NH_4^+ photometrically (determination of a reaction product of NH_4^+ at $\lambda = 660$ nm according to the Dutch standard method NEN 6576; Cary 50 spectrophotometer, Varian) and for Cl^- and NO_3^- by ion chromatography (ICS-90 Dionex). The forest floor samples were dried at 70°C and grinded; samples of the mineral soil were dried at 40°C and sieved (2 mm mesh width). Samples of the FH layer of the forest floor and the mineral soil were analysed for total N (salicylic acid-thiosulphate modification of Kjeldahl method: 1 g soil or 0.2 g ectorganic material in 7 ml $C_7H_6O_3$ solution (50 g dissolved in 1 l H_2SO_4 96%), 5 ml concentrated H_2SO_4, and 0.5 g $Na_2S_2O_3.5H_2O$; Bremner 1996) and total C (estimated by loss on ignition: 4.5 h at increasing temperature until 450°C, then 4 h at 450°C; estimated % C = (100 – % of ashes residue) / 2). The samples of the FH layer were digested (0.2 g organic material in 10 ml HNO_3 and 2 ml $HClO_4$; McKenzie 2010) and the 0-5 cm samples of the mineral soil were extracted with $BaCl_2$ (5.00 g soil in 100 ml 0.1 M $BaCl_2$ solution; Dutch standard method NEN 5738) and were subsequently analysed for Ca^{2+} and Mg^{2+} (flame atomic absorption spectrophotometry, SpectrAA-220, Varian). Wood and foliar material were dried at 70°C, grinded, and following total destruction analysed for total N. The quality of the chemical analyses was checked by including method blanks and repeated measurements of internal standards and certified reference samples.

2.4. Element fluxes, N stocks, and soil properties

Annual throughfall fluxes (kg ha^{-1} y^{-1}) were the sum of monthly fluxes calculated from the concentration in the subsamples multiplied by the monthly throughfall volume in the three collectors and divided by the surface area of the three funnels (Wuyts and others 2008b). Year-round mean NO_3^--N concentrations (mg l^{-1}) were calculated as the mean of NO_3^--N concentrations weighted by the sample volume in the lysimeters on each sampling event. Soil NH_4^+-N and NO_3^--N leaching fluxes (kg ha^{-1} y^{-1}) were determined by multiplying the water seepage flux (l m^{-2} y^{-1}) with the year-round, volume-weighted mean ion concentration in the soil solution (mg l^{-1}). The water seepage fluxes were estimated with the chloride mass balance method (Eriksson and Khunakasem 1969; Boxman and others 2008; De Schrijver and others 2008). Recent studies indicate that Cl^- release or retention may occur in the soil (Öberg and Sandén 2005; Bastviken and others 2007), but we found the mass balance method with Cl^- as a tracer sufficient to study edge effects. The water seepage fluxes in stands Qr2 and Pn2 calculated with Na^+ (flame atomic absorption spectrophotometry, SpectrAA-220, Varian) as a tracer were lower than with Cl^-, but the difference was marginally insignificant (paired samples t test, $P = 0.077$) and the Na^+ and Cl^- concentrations in the soil solution were highly correlated irrespective of time and distance from the edge (Pearson $R = 0.94$; $P < 0.001$; $n = 35$). The calculated water seepage fluxes were independent of edge distance. However, at the first two distance plots at the Qr2 site, the calculated water seepage fluxes at 90 cm soil depth were high and equalled the throughfall volumes (± 600 l m^{-2}), while further down the edge, they were half the volume of throughfall. A small but profound (± 1 m) creek located 2 m before the edge front of stand Qr2 may have influenced subsurface water flows. As a result, DIN throughfall fluxes at the first two distance plots of Qr2 were probably overestimated.

The N stock in leaves or needles was approximated by multiplying the mean N concentration (kg N kg^{-1}) by the LAI (m^2 m^{-2}, converted to m^2 ha^{-1}) and the inverse of the mean SLA. The N stock in tree stem biomass was estimated by multiplying the mean N concentration (kg N kg^{-1}) by the stem volume (m^3 ha^{-1}) and the wood density, which was in general lower at the edge than in the interior.

The C:N ratios were determined for the FH layer of the forest floor ($C{:}N_{FH}$) and the mineral soil ($C{:}N_{0\text{-}5}$, $C{:}N_{5\text{-}10}$, $C{:}N_{10\text{-}30}$). The N stocks (kg N ha^{-1}) in the mineral soil were calculated based on the measured N concentration and soil density (the latter was significantly lower at the edge than in the interior).

2.5. Statistics

By means of a repeated-measures ANOVA (RMA), the effects of within-subject factor ‘distance to the forest edge’ (8 levels) and between-subjects factor ‘forest type’ (2 levels: coniferous and deciduous) on NO_3^--N concentrations in soil water, dissolved inorganic nitrogen (DIN, NH_4^+-N + NO_3^--N) leaching, and soil characteristics (C, N, C:N) were tested. Furthermore, we estimated the mean NO_3^--N concentrations and DIN soil leaching fluxes in the first 64 m of the edge, weighted by the share of each distance plot in the considered zone (i.e., 1, 2, 3, 6, 12, 24, and 16 m for the first to seventh distance plots, respectively). Repeated-measures ANOVA was applied to identify and separate the influence of ‘edge proximity’ (2 levels: forest edge 0-64 m and forest interior at 128 m) and forest type on NO_3^--N concentrations and DIN leaching. This data pooling enabled to make more general conclusions. Although the NH_4^+ throughfall deposition, representing on average 73% of the DIN throughfall deposition, was significantly lower in region 1 than in region 2 by 7 kg N ha^{-1} y^{-1} on average (Wuyts and others 2008b), we observed no significant influence of region and its interaction effects on DIN leaching and N content. The factor region and its interaction effects were therefore omitted from the analyses to decrease the number of parameter estimations. Furthermore, differences between edge (0-64 m) and interior (128 m) were tested for the deciduous and coniferous stands separately with non-parametric related samples tests (Wilcoxon signed ranks test). A repeated-measures analysis (RMA) was applied on the dry weight of the FH layer, the N stock in the mineral soil and the biomass (or LAI), the N concentration, and the N stock in stem wood and leaf/needle to separate the influence of 'edge proximity' (2 levels: edge and interior) and of forest type. Finally, single linear regression models (including constants) were tested between DIN in throughfall deposition, $C:N_{FH}$, and the C:N ratios of the mineral soil on the one hand and the (log-transformed) DIN leaching fluxes at 30 and 90 cm soil depth on the other hand. All statistical analyses were performed using SPSS 15.0.

3. Results

3.1. DIN leaching

Higher NO_3^--N concentrations in soil water occurred in the coniferous stands in comparison with the deciduous ones. For example, in the interior part (128 m) of the studied forests, mean concentrations ± standard error were 14 ± 3 mg l^{-1} at 30 cm and 17 ± 9 mg l^{-1} at 90 cm soil depth in the coniferous stands and 4.2 ± 0.9 mg l^{-1} at 30 cm and 3.3 ± 0.3 mg l^{-1} at 90 cm soil depth in the deciduous stands. Similarly, estimated DIN leaching fluxes were higher in the coniferous than in the deciduous stands, with mean interior fluxes of 35 ± 7 kg N ha^{-1} y^{-1} at 30 cm and 10 ± 5 kg N ha^{-1} y^{-1} at 90 cm soil depth in the coniferous stands and 8 ± 2 kg N ha^{-1} y^{-1} at 30 cm and 7 ± 2 kg N ha^{-1} y^{-1} at 90 cm soil depth in the deciduous stands. However, forest type affected DIN leaching only significantly ($P < 0.05$) at 30 cm soil depth, and yet marginally insignificantly ($0.05 < P < 0.1$) affected the NO_3^--N concentrations at this depth (Table 2).

According to the RMA analysis (Table 2), the distance from the forest edge did not significantly (P > 0.1) influence the NO_3^--N concentrations and the DIN leaching fluxes at 30 and 90 cm depth, indicating that the NO_3^--N concentrations and the DIN leaching did not display a monotonic (increasing or decreasing) relationship with distance from the edge. The NO_3^--N concentrations in the soil water at 30 and 90 cm (Fig. 2, Appendix) were not enhanced at the edges, except for Pn1 at 30 cm depth, where we observed a slight decrease in concentration with increasing edge distance. Instead, the NO_3^--N concentrations were highest between 8 and 32 m or increased towards the forest interior (at both sampling depths in Pn2 and in Qr1 and Ps1at 30 cm). In all stands, except for Pn1 at 30 cm and Qr2, the lowest DIN leaching fluxes occurred at the edge front (0 to 2 m) with values equal or even lower than at 128 m, while maximum values were obtained at 8, 16, 32, or 64 m from the edge (see Appendix). Fig. 2 shows the dissimilarity between the mean edge patterns of DIN throughfall deposition and of DIN leaching fluxes in the deciduous and coniferous stands. While the DIN throughfall deposition decreased with increasing edge distance, the DIN leaching fluxes at 90 cm soil depth increased with distance in the first 20 m of the edge ('outer edge'), peaked at 32 and 64 m, and decreased in the forest interior at 128 m. The DIN leaching at 90 cm soil depth in the first 20 m from the edge was 15 ± 12 and 17 ± 6 kg N ha^{-1} y^{-1} (mean ± SE) in the deciduous and coniferous forest stands, resp., while from 20 to 64 m the leaching amounted to 24 ± 9 and 36 ± 11 kg N ha^{-1} y^{-1}, resp. No significant interaction between forest type and distance from the forest edge occurred for NO_3^--N concentrations and DIN leaching at 30 and 90 cm (Table 2).

The NO_3^--N concentrations and leaching of DIN averaged over the first 64 m of the edge were consistently higher than the concentrations and fluxes in the interior, and differences were marginally insignificant for the leaching fluxes at 30 cm and significant for those at 90 cm (Table 2). The differences in NO_3^--N concentrations were, however, not significant. When considering coniferous and deciduous stands separately, NO_3^--N concentrations and DIN leaching did not differ significantly between the first 64 m of the edge and the interior, although the difference in DIN leaching flux at 90 cm in the coniferous stands was only marginally insignificant. In the first 64 m of the edges, the DIN leaching fluxes at 30 cm soil depth were in the deciduous stands, on average, 10 kg N ha^{-1} y^{-1} (125%) higher than in the forest interior and in the coniferous stands 24 kg N ha^{-1} y^{-1} (69%) higher than in the interior (Table 2). At 90 cm soil depth, the increase in DIN leaching in the 64 m edge zone relative to the interior was 14 kg N ha^{-1} y^{-1} (or 181%) and 21 kg N ha^{-1} y^{-1} (or 105%) in the deciduous and coniferous stands, respectively (Table 2). For comparison, we provide the results of the repeated measures analysis on DIN throughfall deposition and its weighted-means in the 64-m edge zone and the interior of the deciduous and coniferous stands in Table 2.

Significant linear relations were found between NO_3^--N concentrations at 30 and 90 cm ($R^2 = 0.57$; $P < 0.001$; slope = 1.982) and between the log-transformed DIN leaching fluxes at 30 and 90 cm ($R^2 = 0.51$; $P < 0.001$; slope = 0.952). The DIN leaching fluxes at 30 cm and 90 cm were plotted against the DIN in throughfall deposition in Fig.3. The DIN leaching fluxes at 30 cm were significantly linearly related with the DIN input via throughfall deposition ($R^2 = 0.43$; $P < 0.001$; slope = 1.51; Fig. 3). This relationship held when the deciduous stands were considered separately ($R^2 = 0.33$; $P = 0.001$; slope = 1.79) but was marginally insignificant for the coniferous stands ($R^2 = 0.14$; $P = 0.073$; slope = 1.05). The linear relationship between DIN throughfall deposition and DIN leaching was improved in the coniferous stands when only plots with $C{:}N_{FH} \leq 25$ (n=18) were considered ($R^2 = 0.32$; $P = 0.014$; slope = 1.70). No significant linear relationships were observed between the DIN throughfall deposition and the DIN leaching at 90 cm ($P = 0.138$, 0.316, and 0.377 for all (n = 40), the deciduous (n = 16), and the coniferous (n = 24) stands, respectively).

3.2. Forest floor and mineral soil

At the outer edges (0-20 m), on average 7.5 ± 0.7 kg m^{-2} of dry FH layer was collected, which was significantly lower than in the forest interiors (10.9 ± 1.4 kg m^{-2}; Table 3). A significant effect of forest type was observed on the C concentrations and the C:N ratio of the FH layer (Table 4), which were both higher in the deciduous than in the coniferous stands. The distance from the edge significantly affected the C and N concentrations in the FH layer of the forest floor, as well as its C:N ratio (Table 4). The overall trend was that the N and C concentrations and the C:N ratios were lower at the edges (Fig. 4). No significant interactions between edge effects and forest type were detected in the FH layer.

The N concentrations in the mineral soil were in general higher at the edges in all soil depths but were significantly influenced by edge effects only in the 0-5 cm mineral topsoil and marginally insignificantly at 10-30 cm (Table 4; Fig. 4). The C concentrations in the soil were significantly affected by distance from the edge in all sampled soil depths (Table 4; Fig. 4), with higher concentrations near the edge. The C:N ratios of the mineral topsoil (0-5 cm) were significantly lower at the edge. The forest type had a significant effect on the N concentrations of the 0-5 cm and 5-10 cm mineral soil layers and the C:N ratios of the 0-5 cm mineral topsoil and had a marginally insignificant effect on the C:N ratios of the 5-10 and 10-30 cm mineral soil layers (Table 4), with higher N concentrations and lower C:N ratios in the deciduous stand. No significant interaction effects between forest type and edge distance were observed in the mineral soil.

The N stocks in the mineral soil at 0-5 cm, 5-10 cm, and 10-30 cm depth were, on average, 376 (or 49%), 148 (or 28%), and 419 (or 25%) kg ha^{-1} higher at the outer edge than in the forest interior, respectively, the difference being significant for the 0-5 cm topsoil and marginally insignificant in the other mineral soil layers (Table 3). When the deciduous and coniferous stands were considered separately (Table 3), the pattern was consistent but less outspoken, with only marginally insignificant differences at 0-5 cm and 5-10 cm depth in the deciduous stands and at 0-5 cm depth in the coniferous stands. Summed over the total sampled mineral soil layer (0-30 cm), differences in the soil N stock between outer edge and interior were larger in the deciduous forest types (1232 kg ha^{-1}, i.e., 427, 176, and 629 kg ha^{-1}, for the increasing soil depth ranges) than in the coniferous ones (652 kg ha^{-1}, i.e., 325, 119, and 208 kg ha^{-1}, for the increasing soil depth ranges). The N stocks in the mineral soil did not differ significantly between the coniferous and the deciduous stands for any of the sampling depths (Table 3).

Plotting the DIN leaching fluxes at 30 and 90 cm soil depth against the C:N ratio of the FH layer (C:N$_{FH}$) and the mineral topsoil (C:N$_{0\text{-}5}$) (Fig. 3) showed distinct clusters related to the forest type, e.g., in the deciduous stands, similar DIN leaching occurred at lower C:N$_{FH}$ ratios than in the coniferous stands. In both forest types, the DIN leaching at 30 cm soil depth was not significantly related to the C:N ratios. The DIN leaching at 90 cm depth in the deciduous stands was marginally insignificantly related to C:N$_{FH}$ ($R^2 = 0.19$; $P = 0.097$; slope = -7.93), but significantly negatively related to C:N$_{0\text{-}5}$ ($R^2 = 0.35$; $P = 0.015$; slope = -3.03), C:N$_{5\text{-}10}$ ($R^2 = 0.51$; $P = 0.002$; slope = -1.90), and C:N$_{10\text{-}30}$ ($R^2 = 0.38$; $P = 0.012$; slope = -1.72) soil layers. The relationship between DIN leaching at 90 cm depth and C:N$_{FH}$ disappeared when the extreme point at C:N$_{FH}$ = 16.4 (see Fig. 3) was removed ($R^2 = 0.02$, $P = 0.636$). In the coniferous stands, relations of DIN leaching at 90 cm with neither C:N$_{FH}$ nor the C:N ratios of the mineral soil were significant. Linear regression on log-transformed DIN leaching values yielded higher P and R^2 values for the relation between DIN leaching at 90 cm and the C:N ratio at 0-5 cm ($R^2 = 0.48$; $P = 0.003$) and 5-10 cm ($R^2 = 0.63$; $P < 0.001$) of the mineral soil in the deciduous stands.

3.3. N in stems and fresh foliar material

The LAI and stem volume were generally higher in the first 20 m of the edges than in the interior, the differences being marginally insignificant for LAI and significant for stem volume (Table 3). The N concentrations in stem wood and foliar material differed not significantly between the forest edge and the interior (Table 3).

The N stock in the foliar material (Table 3) was, on average, 3 kg N ha^{-1} (21%) higher in the first 20 m of the edge (mean 20 kg N ha^{-1}) than in the interior (mean 16 kg N ha^{-1}). In stem biomass, on average, an additional amount of 27 kg N ha^{-1} (20%) was stored in the first 20 m of the edge (average 162 kg N ha^{-1}) in comparison with the interior (average 136 kg N ha^{-1}). In the deciduous stands, the mean difference was 5 kg N ha^{-1} in foliar biomass and 22 kg N ha^{-1} in stem biomass. The differences between edge and interior in the coniferous stands amounted to 2 kg N ha^{-1} in foliar biomass and 32 kg N ha^{-1} in stem biomass. However, the effect of edge proximity was not significant, even when forest types were considered separately (Table 3). The N stock in foliar material and stem wood was not significantly affected by forest type (Table 3).

4. Discussion

4.1. Forest type effect on DIN leaching

Higher NO_3^--N concentrations in soil water and DIN leaching occurred in the coniferous pine stands than in the deciduous oak and birch stands, a result in line with previous studies performed in the interior of similar forest types (Herrmann and others 2005; De Schrijver and others 2004, 2008) and deciduous and coniferous forest types in general (von Wilpert and others 2000; Rothe and others 2002; De Schrijver and others 2007b). Gundersen and others (1998), MacDonald and others (2002), and De Schrijver and others (2007b) demonstrated a positive relationship between DIN leaching and N deposition at N saturated sites. This would imply that the forest type effect on DIN leaching would be related primarily to differences in atmospheric N input. Although the species-related difference in DIN leaching increases with the difference in N throughfall deposition or N load (Rothe and others 2002; De Schrijver and others 2007b), stand history, N uptake, soil N retention, and gaseous N losses may surpass the deposition effect (Rothe and others 2002).

The deciduous stands had lower C:N ratios in both the FH layer of the forest floor ($C:N_{FH}$) and the the mineral topsoil (0-5 and 5-10 cm) than the coniferous stands, in accordance with Kristensen and others (2004) and Gundersen and others (2009). Dise and others (1998), Gundersen and others (1998, 2009), and MacDonald and others (2002) suggested the use of N input and the C:N ratio of the forest floor or mineral topsoil to predict NO_3^- leaching. In our coniferous stands, DIN leaching at 30 and at 90 cm were related with neither N input nor C:N ratios. However, DIN leaching at 30 cm related significantly with DIN throughfall deposition in the coniferous stands when only plots with $C:N_{FH} \leq 25$ were considered. This result would confirm the finding of Gundersen and others (1998, 2009) and MacDonald and others (2002) that in coniferous stands for organic layer $C:N \leq 25$ DIN leaching is related to DIN input, although the slope of DIN leaching vs. DIN throughfall is higher than 1. In the deciduous stands, DIN leaching was significantly negatively related with C:N ratios of the 0-5, 5-10, and 10-30 cm soil layers. Our study supports the finding of Gundersen and others (2009) that a C:N value of the organic layer of 25 is not a useful threshold value to discriminate between low and high risk of DIN leaching in deciduous stands. Gundersen and others (2009) suggested that the C:N ratio of the mineral topsoil (0-10 cm) better reflects the N status of mull type soils - in their study related to deciduous stands - and that the organic layer C:N may be better suited for mor and moder type soils.

When analysing the effect of forest type on biogeochemical fluxes, stands should meet the prerequisite of comparable climate, air pollution level, soil type, land-use history, and successional stage (De Schrijver and others 2007b). Our study examined forest stands on the same soil type and, within one region, under similar air quality and climate conditions. Land-use history was alike for all stands down to 1770, except for the Qr1 stand, which was shortly managed as grassland around 1900. Soil pH, soil N, nitrification rates, and NO_3^- leaching can remain elevated and soil C concentration and C:N ratios lowered in post-agricultural forests, even a century after agricultural abandonment (Compton and Boone 2000; Jussy and others 2002; Gundersen and others 2009). However, on sandy soils and after more than 50 years of reforestation, tree species rather than land-use history affects N cycling (Compton and others 1998). In the 90-year old Qr1 stand, soil pH-KCl was higher than in the other forest stands (Table 1), but C:N ratios of the mineral topsoil (on average 17.7 in the 128 m plot) were comparable to those in the other oak stand Qr2 (on average 18.6 in the 128 m plot). Moreover, DIN leaching fluxes in the Qr1 stand were not higher than in the

Qr2 stand, which suggests a limited effect of the former grassland management on soil N cycling in Qr1. Canopy closure was complete in all stands, but while all stands were in timber stage, the birch stands Bp1 and Bp2 were in late pole stage. The trees in the birch stands are close to the culmination point of height growth. Further development of these stands will be characterised by an increase in N deposition input, due to increasing tree height (Draaijers 1993), and a decrease in N accumulation in biomass, since after canopy closure the most N-rich biomass compartments (canopy foliage) are synthesised (Richter and others 2000), and this can result in a slight increase in DIN leaching (Hansen and others 2007).

4.2. Edge effect on DIN leaching

In comparison with the forest interior, enhanced leaching fluxes of DIN are found in the 64-m edge zone of both the coniferous and deciduous forests. These differences in DIN leaching between the 64-m edge zone and the interior are larger than these in DIN throughfall deposition because the most pronounced enhancement of DIN throughfall deposition is restricted to the first 20 m of the edge while the enhancement of DIN leaching occurs between 16 and 64 m from the edge. The increase in DIN soil leaching in the 64-m edge zone was greatest in the coniferous forests, and this for both sampling depths, in accordance with the more pronounced edge effects on DIN throughfall deposition in the coniferous forests than in the deciduous ones (Wuyts and others 2008a, b). Below 90 cm, an additional 14 kg N ha^{-1} y^{-1} and 21 kg N ha^{-1} y^{-1} was leached in the 64-m edge zone in the deciduous and coniferous forests in comparison with the forest interior. However, for DIN leaching as well as for the other variables considered (soil N and C concentrations and N stocks) we found no significant difference in edge effects between the coniferous and deciduous forest types.

The patterns of DIN leaching and NO_3^--N concentration did not univocally reflect the patterns of DIN throughfall deposition (Fig. 2). In the *Q. robur*, *B. pendula*, and *P. nigra* stands, maximum DIN throughfall deposition occurred at the front of the edges (0-2 m from the edge) behind which deposition decreased with increasing edge distance (Wuyts and others 2008b; Fig. 2). In the Ps1 stand, edge effects on throughfall deposition of DIN were not observed because the edge of the Ps1 stand borders a very busy motorway: trucks passing by at < 5 m from the edge considerably disturb the expected pattern of wind speed and turbulence across forest edges. We found no evidence of higher NO_3^--N concentrations in the soil water near the exposed edges and remarkably low DIN leaching occurred in the outer edge (the first 0-20 m of the edge) of the stands. At 30 cm soil depth, soil DIN leaching was significantly related to the DIN throughfall deposition, but at 90 cm, the relationship with throughfall was lost. The DIN leaching fluxes at 90 cm soil depth increased with distance in the first 20 m of the edge until the highest values were reached at 32 and 64 m, and decreased again in the forest interior at 128 m. In the first meters of an exposed beech edge, Kinniburgh and Trafford (1996) reported very low NO_3^--N concentrations in the pore water beneath the rooting zone; however, concentrations were increased at 30-100 m from the edge, after which they decreased again. These results and those of Spangenberg and Kölling (2004) agree with our findings on leaching of DIN. The non-uniform response of DIN leaching to edge proximity is probably the result of a complex interaction of several processes: (i) N uptake by trees and the understory vegetation, (ii) gaseous N loss, (iii) N immobilisation in the soil, and (iv) dissolved organic N (DON) leaching. However, because not all possible N pathways were actually measured in this study, we stress the importance of further research to verify our assumptions.

We avoided the influence of N uptake by understory vegetation on DIN leaching, except in the Pn2 stand, where lower DIN leaching at the edges may be related to N uptake by grasses at the edge. Also, in stand Qr1, the brambles that remained outside the cleared zone around the lysimeters might still have affected DIN leaching in the first 20 m of the edge to a minor extent. Yet, the effect of these brambles can be assumed negligible as their abundance was low. The stand volume and the LAI were higher in the first 20 m of the edge, but differences in N stock in these biomass compartments were not significant. So, though we did not measure N stocks in all biomass compartments, these results do not confirm the hypothesis by Spangenberg and Kölling (2004) on N sequestration in trees and understory biomass and instead indicate that the role of higher N accumulation in biomass in lower DIN leaching in the outer edge is limited.

Production of NO and N_2O, primarily driven by microbial processes, depends on soil temperature, moisture, pH, and N input (Butterbach-Bahl and others 2002; Schindlbacher and others 2004; Pilegaard and others 2006). From edge gradients in N throughfall deposition, pH, and microclimate (e.g., soil temperature; Chen and others 1995), elevated N loss through NO and N_2O emission can be expected at edges.

N concentrations in the mineral topsoil (0-5 cm) were significantly enhanced at the edges and the N stock in the total sampled mineral soil (0-30 cm) was, on average, 951 kg N ha^{-1} higher in the first 20 m of the edge than in the interior. Processes that are believed to be involved in N retention in the soil are (a)biotic fixation of NO_3^- and NH_4^+ in or on soil organic matter (Magill and others 1997; Aber and others 1998; Davidson and others 2003; Micks and others 2004; Morier and others 2008). NH_4^+ adsorption in the mineral soil is positively related to soil pH and exchangeable amounts of Mg^{2+} (Kothawala and Moore 2009), which were both enhanced in the mineral topsoil (0-5 cm) in the first 32 m of our edges (data on Mg^{2+} in Fig. 4). Moreover, Hayes (2002) suggested that at forest edges a complex interaction of processes is involved in soil N retention, such as increased litter decomposition and higher biomass input through litterfall. The magnitude and extent of the edge effects on these processes may differ between edges with dissimilar structure, species composition, exposition, and type of adjacent land cover (Hayes 2002; Malmivaara-Lämsä and others 2008). We presume that both litter decomposition and litterfall input are increased at the edges, but that the edge effect on the decomposition rate penetrates the forest deeper than the effect on litterfall. Litter decomposition depends, among other factors, on soil biological activity. Higher soil temperature, occurring up to 50-60 m from the edge (Chen and others 1995; Heithecker and Halpern 2007), and higher Ca content in the litter (Fig. 4), as a result of higher base cation deposition (Wuyts and others

2008a), could favour the abundance and activity of soil and litter organisms and increase decomposition rates at the edges (Reich and others 2005; Hobbie and others 2007). Hence, we hypothesize that with an increase in litter decomposition, less N is retained in the forest floor and more N is flushed to the mineral soil up to 64 m from the edge. At our edges, though LAI was higher, the FH layer dry weight at the edge was on average 28% lower than in the interior, which can be related to higher decomposition rates but also to blow up of litter by wind from the edge to the interior. Next, we presume the presence of an edge effect on litterfall input that penetrates the edge less far than the edge effect on decomposition. In the outer 20 m of the edges, the biomass of fresh leaves (LAI), and presumably also the litterfall flux to the forest floor, was higher than further down the edge and in the interior. The soil organic matter content was enhanced near the edges, indicating a higher potential for N immobilisation in or on soil organic matter. Also Marchand and Houle (2006) observed a higher soil organic matter content in the first 20 m of a forest edge. In the outer edge of a *P. nigra* stand near Pn2, Vandenbruwane (2008) found higher DON and dissolved organic C (DOC) fluxes from the forest floor to the mineral soil and higher retention of DON and DOC in the upper 70 cm of the mineral soil in the outer edge than in the interior (13 vs. 7 kg N ha^{-1} y^{-1}). Next to higher DON retention, Vandenbruwane (2008) observed higher DON leaching fluxes below the main rooting zone in the outer edge than in the interior (5 vs. 3 kg N ha^{-1} y^{-1}). Hence, the proportion of organic N in the total N leaving the system via leaching is increased at the outer edge in comparison with the interior.

We can conclude that the C:N ratio and the DIN input with throughfall deposition cannot serve as indicators or predictors for DIN leaching in forest edges: at the outer edges, higher DIN throughfall deposition and lower C:N ratios were observed, yet lower DIN leaching was detected in comparison with the plots at 32 and 64 m from the edge, particularly at 90 cm soil depth. Although we found a significant relationship between DIN throughfall and DIN leaching at 30 cm in the deciduous stands (and in the coniferous stands for $C:N_{FH} \leq 25$), such relationships were no longer appreciable at 90 cm soil depth. Between DIN leaching and C:N ratio, only significant relationships were found in the deciduous stands, and the variability in DIN leaching explained by the C:N ratio of the mineral soil was low.

4.3. Methodological considerations

The use of only one suction cup lysimeter per depth and distance plot may not take into account the spatial variability in DIN leaching at a given edge distance. Kohlpaintner and others (2009) found that only understory vegetation coverage, distance to the nearest tree, and tree basal area within a radius of 4 m contributed to explain the variability in NO_3^- leaching in a mature Norway spruce stand. Given that in our stands, (i) understory vegetation was absent or removed more than half a year before sampling (in exception of the Pn2 stand, where a homogeneous grass cover occurred at the edge), and (ii) forest stands were homogeneous in basal area, with exception of the edge front, we expect spatial variability in DIN leaching within one distance plot to be limited. The good agreement (high correlation) in NO_3^--N concentrations and DIN leaching between the lysimeters of the two sampling depths (with at least 1 m intermediate distance) also suggests a relatively low spatial variability.

The DIN leaching fluxes were calculated with water percolation fluxes estimated from the chloride mass balance. Although Cl^- acts as a conservative element in the soil of undisturbed forests in the long term (Kauffman and others 2003) and is even close to conservative within 2 years (Rosenqvist and others 2010), imbalances between Cl^- input and output within one year and periods of sea salt peaks may occur, causing the water percolation flux and DIN leaching to be under- or overestimated. In this study, the water percolation fluxes might be overestimated due to a peak in sea salt deposition that occurred during a storm event on 25 November 2005, particularly in the region the closest to the sea (region 1). Although this peak in Cl^- deposition occurred in the beginning of the year of sampling, it may not have passed completely through the soil by the end of the sampling period. However, the similar trend in the measured NO_3^--N concentrations in the soil solution as in the derived DIN leaching fluxes and the large number of studied stands and distance plots reduce the uncertainty in the edge pattern of DIN leaching related to the use of the chloride mass balance.

5. Conclusions

In 64 m edge zones of deciduous and coniferous forests, DIN leaching fluxes were higher than in forest interiors. DIN leaching was higher and exhibited the largest edge effects in coniferous forests. DIN leaching at 90 cm soil depth did not relate with DIN throughfall deposition; in the first 20 m (i.e., the outer edge), DIN leaching was reduced in comparison with further down the edge (20-64 m). Increased soil N retention is probably one of the processes involved in this local decrease in DIN leaching. Our results point towards a complex of edge effects on biogeochemical processes, a result of interactions between edge effects on N deposition and on base cation deposition, microclimate, and tree dynamics (e.g., growth and litterfall). The course and extent of these edge effects may differ according to structure, exposition, species composition, and adjacent land cover, complicating the generalisation of edge patterns in biogeochemical and ecological studies.

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Appendix

Throughfall deposition and soil leaching fluxes at 30 cm (DIN leaching$_{30}$; indicated by bars) and 90 cm (DIN leaching$_{90}$; bars) soil depth of DIN (NO_3^- + NH_4^+; kg N ha^{-1} y^{-1}) and volume-weighted mean NO_3^--N concentrations (mg l^{-1}; crosses) in the soil solution along transects across the studied forest edges. Soil leaching fluxes at 90 cm were not measured in the stands Qr1 and Bp1 due to high ground water tables. Data on throughfall deposition were previously published by Wuyts and others (2008b), except for Ps1. Note the higher y-axis limit for the stands Qr2, Pn1, Pn2 and Ps1.

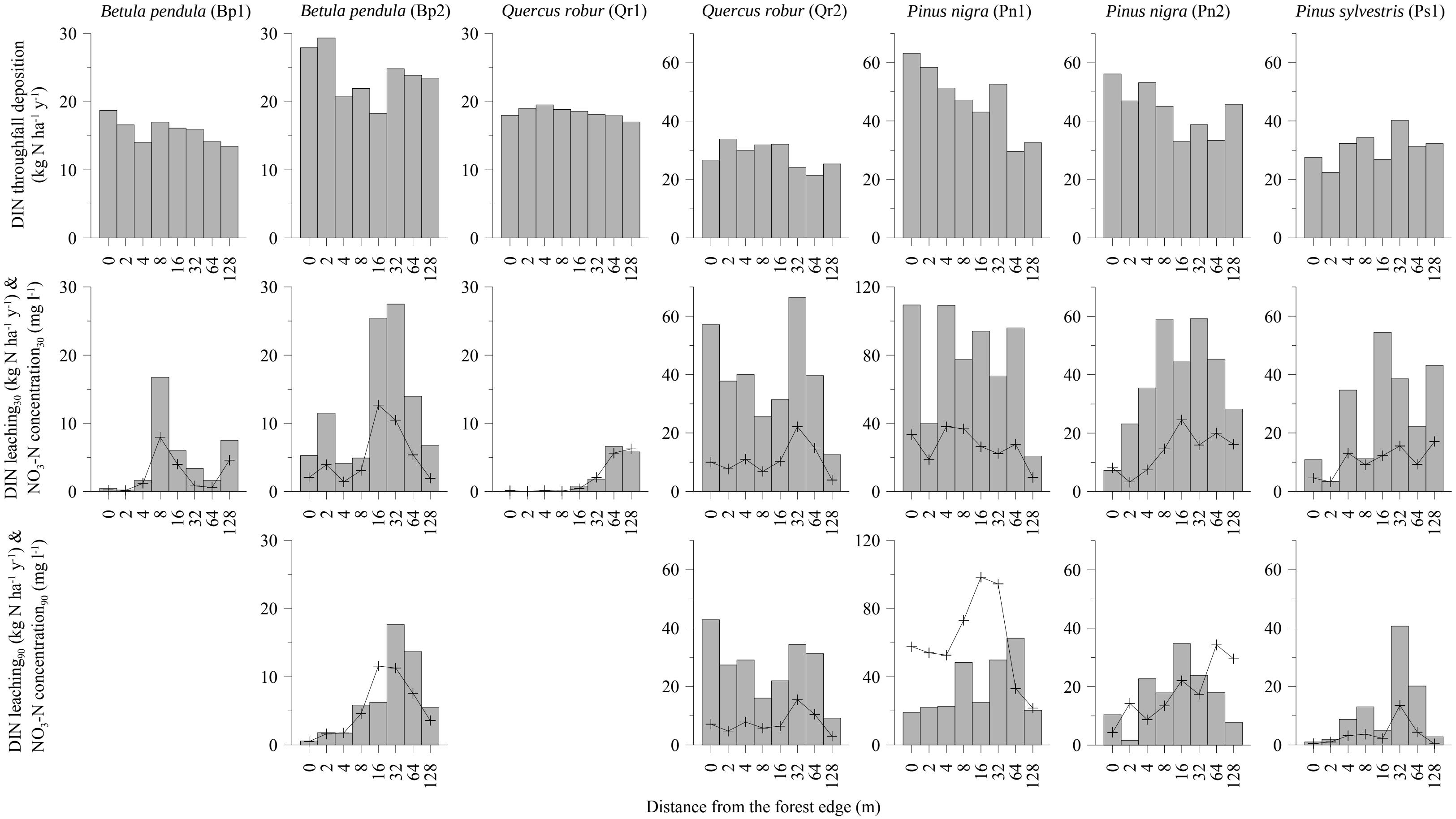

Figure legends

Fig. 1. Maps indicating location of Flanders within Europe and the eight studied forest stands in the two regions (see Table 1 for explanation of site codes).

Fig. 2. Mean throughfall deposition of DIN (NH_4^+ + NO_3^-; kg N ha^{-1} y^{-1}) and DIN soil leaching fluxes (kg N ha^{-1} y^{-1}) and NO_3^--N concentrations (mg l^{-1}) in the soil solution at 30 (DIN $leaching_{30}$ and NO_3^--N $concentration_{30}$) and 90 cm (DIN $leaching_{90}$ and NO_3^--N $concentration_{90}$) soil depth along transects across the deciduous and coniferous forest sites. Error bars indicate standard errors. Note the altered y-axis limits.

Fig. 3. DIN leaching (kg N ha^{-1} y^{-1}) at 30 and 90 cm soil depth plotted against the throughfall deposition of DIN (kg N ha^{-1} y^{-1}) and the C:N ratio of the fermentation and humus layer of the forest floor ($C:N_{FH}$) and of the 0-5 cm mineral topsoil ($C:N_{0-5}$) in the separate distance plots in the deciduous stands (●) and the coniferous ones (+). Indicated are the (marginally) significant relationships. All data included, except for the Ps2 stand.

Fig. 4. Mean N (g kg^{-1}) and C (%; determined by loss on ignition) concentrations and C:N ratios of the fermentation and humus layer (FH) of the forest floor and the 0-5 cm, 5-10 cm, and 10-30 cm of the mineral soil and mean Ca and Mg concentrations of the FH layer (mol_c kg^{-1}) and exchangeable concentrations in the top 5 cm of the mineral topsoil ($mmol_c$ kg^{-1}) along transects across the forest edges of all the studied forest stands. Error bars indicate standard errors. Note the altered y-axis limits for the forest floor and the different soil depths.

Tables

Table 1.

Site code	Location		Tree species	Age	SN	BA	V	H	H_{dom}	LAI		pH-KCl
				(y)	(ha^{-1})	(m^2 ha^{-1})	(m^3 ha^{-1})	(m)	(m)	Summer	Winter	
Bp1	51°09'22"N	03°04'48"E	*Betula pendula*	30-40	3628	26	194	11.2	18.2	1.36	0.61	2.93
			Sorbus aucuparia[+]		389	2	5					
Bp2	51°25'56"N	05°00'31"E	*Betula pendula*	20-30	2715	13	74	8.1	13.8	1.33	0.31	3.03
			Quercus robur[Λ]		111	3	34					
Qr1	50°52'08" N	03°27'59"E	*Quercus robur*	90	187	31	343	24.2	26.4	1.90	0.79	3.35
Qr2	51°24'44" N	05°02'45"E	*Quercus robur*	68	135	23	221	21.1	22.4	1.88	0.40	2.88
Pn1	51°08'26"N	03°06'36"E	*Pinus nigra* ssp. *laricio*	65	388	36	336	19.2	22.0	2.04	-	2.91
Pn2	51°26'37"N	05°05'14"E	*Pinus nigra* ssp. *nigra*	43	1162	55	488	17.3	19.1	1.80	-	2.89
Ps1	51°10'11"N	03°09'36"E	*Pinus sylvestris*	80	458	29	287	19.8	23.2	1.82	-	2.95
Ps2	51°24'45"N	05°02'39"E	*Pinus sylvestris*	76	195	20	183	19.4	21.1	1.03	-	2.86

[+]: sum of basal area of other species (*Quercus robur* and *Rhamnus frangula*) < 1 m^2 ha^{-1}

[Λ]: sum of basal area of other species (*Robinia pseudo-acacia* and *Quercus rubra*) < 1 m^2 ha^{-1}

Table 2.

	TF	Leaching 30 cm		Leaching 90 cm	
		$[NO_3^-\text{-}N]$	DIN flux	$[NO_3^-\text{-}N]$	DIN flux
RMA	P value	P value	P value	P value	P value
Factor					
Distance to the forest edge (8)	0.021	0.161	0.281	0.500	0.341
Forest type (2)	0.015	0.054	0.041	0.413	0.462
Distance x forest type	0.211	0.688	0.379	0.960	0.624
Edge proximity (2)		0.339	0.090	0.391	0.003
Forest type (2)		0.002	0.005	0.328	0.383
Edge proximity x forest type		0.788	0.440	0.391	0.223

	TF	Leaching 30 cm		Leaching 90 cm	
		$[NO_3^-\text{-}N]$	DIN flux	$[NO_3^-\text{-}N]$	DIN flux
WSR	(kg N ha^{-1} y^{-1})	(mg l^{-1})	(kg N ha^{-1} y^{-1})	(mg l^{-1})	(kg N ha^{-1} y^{-1})
Forest type					
Deciduous	21 ± 2	7.0 ± 3.2	18 ± 10	9.8 ± 1.0	21 ± 9
0-64 m	20 ± 3	4.2 ± 0.9	8 ± 2	3.3 ± 0.3	7 ± 2
128 m					
Coniferous					
0-64 m	39 ± 3	19 ± 4	55 ± 15	34 ± 20	*31 ± 8*
128 m	37 ± 4	14 ± 3	31 ± 7	17 ± 9	*10 ± 5*

Table 3.

	FH layer	Mineral soil - N stock			Stem wood			Foliar material		
	dry weight	0-5 cm	5-10 cm	10-30 cm	Biomass	[N]	N stock	LAI	[N]	N stock
RMA	P value	P value	P value	P value	P value	P value	P value	P value	P value	P value
Factor										
Edge proximity (2)	0.044	0.003	0.078	0.091	0.043	0.352	0.131	0.058	0.394	0.188
Forest type (2)	0.711	0.542	0.232	0.351	0.117	0.003	0.830	0.808	0.009	0.943
Edge prox. x forest type	0.431	0.530	0.692	0.844	0.294	0.049	0.729	0.880	0.010	0.454

	FH layer	Mineral soil - N stock (kg N ha^{-1})			Stem wood			Foliar material		
	dry weight	0-5 cm	5-10 cm	10-30 cm	Biomass	[N]	N stock	LAI	[N]	N stock
WSR	(kg m^{-2})				(m^{3} ha^{-1})	(mg kg^{-1})	(kg N ha^{-1})	(m^{2} m^{-2})	(g kg^{-1})	(kg N ha^{-1})
Forest type										
Deciduous										
0-20 m	7.5 ± 1.1	*1218 ± 159*	*778 ± 118*	2259 ± 225	193 ± 54	*1140 ± 67*	*158 ± 42*	2.0 ± 0.1	26.5 ± 0.5	20.2 ± 1.4
128 m	9.8 ± 0.4	*791 ± 142*	*602 ± 85*	1630 ± 346	176 ± 55	*987 ± 29*	*126 ± 40*	1.6 ± 0.2	25.2 ± 0.9	15.1 ± 1.7
Coniferous										
0-20 m	7.5 ± 0.9	*1056 ± 130*	584 ± 74	1980 ± 275	*370 ± 81*	629 ± 63	166 ± 47	1.9 ± 0.4	15.6 ± 1.7†	18.8 ± 4.6
128 m	11.6 ± 2.0	*732 ± 90*	466 ± 118	1772 ± 252	*327 ± 62*	693 ± 91	145 ± 46	1.5 ± 0.2	17.5 ± 1.4†	17.2 ± 4.1

†: current-year needles: 17.9 ± 1.9 and 19.8 ± 1.6 g N kg^{-1} at 0-20 m and 128 m, resp.

723 Table 4.

Variable	Factor	FH	Mineral soil		
			0-5 cm	5-10 cm	10-30 cm
N	Distance to the forest edge (8)	**0.011**	**<0.001**	0.130	0.078
	Forest type (2)	0.726	**0.037**	**0.030**	0.441
	Distance x forest type	0.631	0.205	0.086	0.811
C (LOI)	Distance to the forest edge (8)	**0.008**	**<0.001**	**0.021**	**0.014**
	Forest type (2)	**0.044**	0.517	0.223	0.570
	Distance x forest type	0.578	0.312	0.086	0.313
C:N	Distance to the forest edge (8)	**0.002**	**0.023**	0.516	0.125
	Forest type (2)	**<0.001**	**0.003**	0.080	0.062
	Distance x forest type	0.313	0.171	0.163	0.933

Table legends

Table 1. Studied sites (forest stands) with indication of their location, the tree species, and the mean leaf area index (LAI) and pH-KCl (1 M KCl) of the mineral topsoil (0-5 cm) in the forest interior. The mean age, stem number (SN), mean and dominant tree height (H and H_{dom}, respectively), basal area (BA), and stand volume (V) are given for the dominant tree species of each stand.

Table 2. Overview of (i) the repeated-measures ANOVA outcome (RMA; P values) and (ii) the weighted-mean values (± standard error) in the first 64 m of the forest edge (0-64 m) and in the forest interior (128 m) in the deciduous and coniferous forest stands for the NO_3^--N concentrations in soil water ([NO_3^--N]) and DIN leaching at 30 and 90 cm soil depth. Italic: marginally insignificant difference ($0.05 < P < 0.10$) according to Wilcoxon signed ranks (WSR) tests.

Table 3. Overview of (i) the repeated-measures ANOVA outcome (RMA; P values) and (ii) the weighted-mean values (± standard error) in the outer forest edge (0-20 m) and in the forest interior (128 m) in the deciduous and coniferous forest stands for the dry weight of the fermentation and humus layer (FH) of the forest floor, the N stock in the mineral soil (depths 0-5 cm, 5-10 cm, and 10-30 cm), the biomass, N concentration ([N]), and N stock in tree stems, and the leaf area index (LAI), N concentration, and N stock in tree foliar material (leaves and old needles). Italic: marginally insignificant ($0.05 < P < 0.10$) difference between edge and interior according to Wilcoxon signed ranks (WSR) tests.

Table 4. Significance (P value) of edge effects (factor 'distance to the forest edge'), forest type effects, and their interaction ('Distance x forest type') on the C (estimated by loss on ignition, LOI) and N concentration and the C:N ratio of the fermentation and humus layer (FH) of the forest floor and the mineral soil according to a repeated-measures ANOVA (bold: $P < 0.05$).

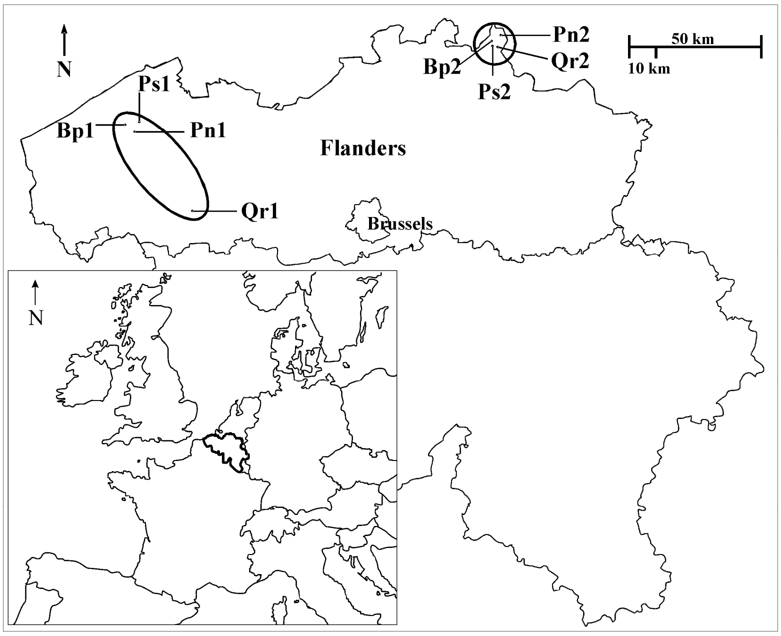
N
Ps1
Bp1
Pn1
Qr1
Flanders
Brussels
Pn2
Bp2
Qr2
Ps2
50 km
10 km
N

Fig. 1

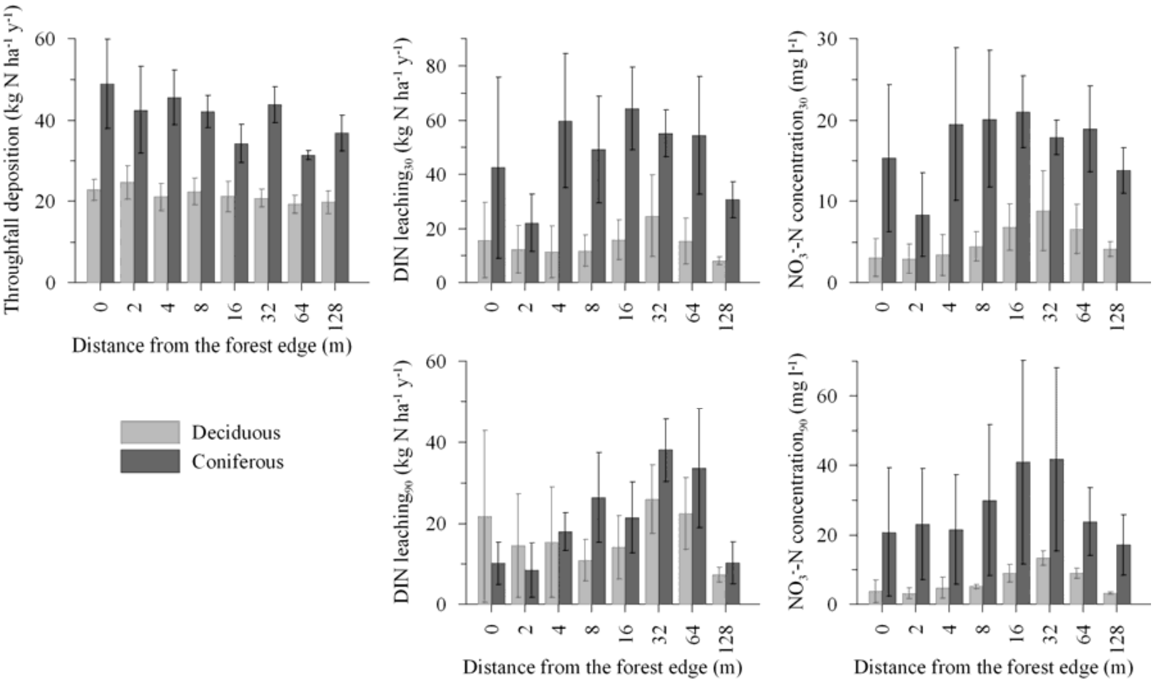
Throughfall deposition (kg N ha^{-1} y^{-1})
0
20
40
60
0
2
4
8
16
32
64
128
Distance from the forest edge (m)
DIN leaching$_{30}$ (kg N ha^{-1} y^{-1})
0
20
40
60
80
NO$_3^-$-N concentration$_{30}$ (mg l^{-1})
0
10
20
30
Deciduous
Coniferous
DIN leaching$_{90}$ (kg N ha^{-1} y^{-1})
0
20
40
60
NO$_3^-$-N concentration$_{90}$ (mg l^{-1})
0
20
40
60
Distance from the forest edge (m)
Distance from the forest edge (m)

Fig. 2

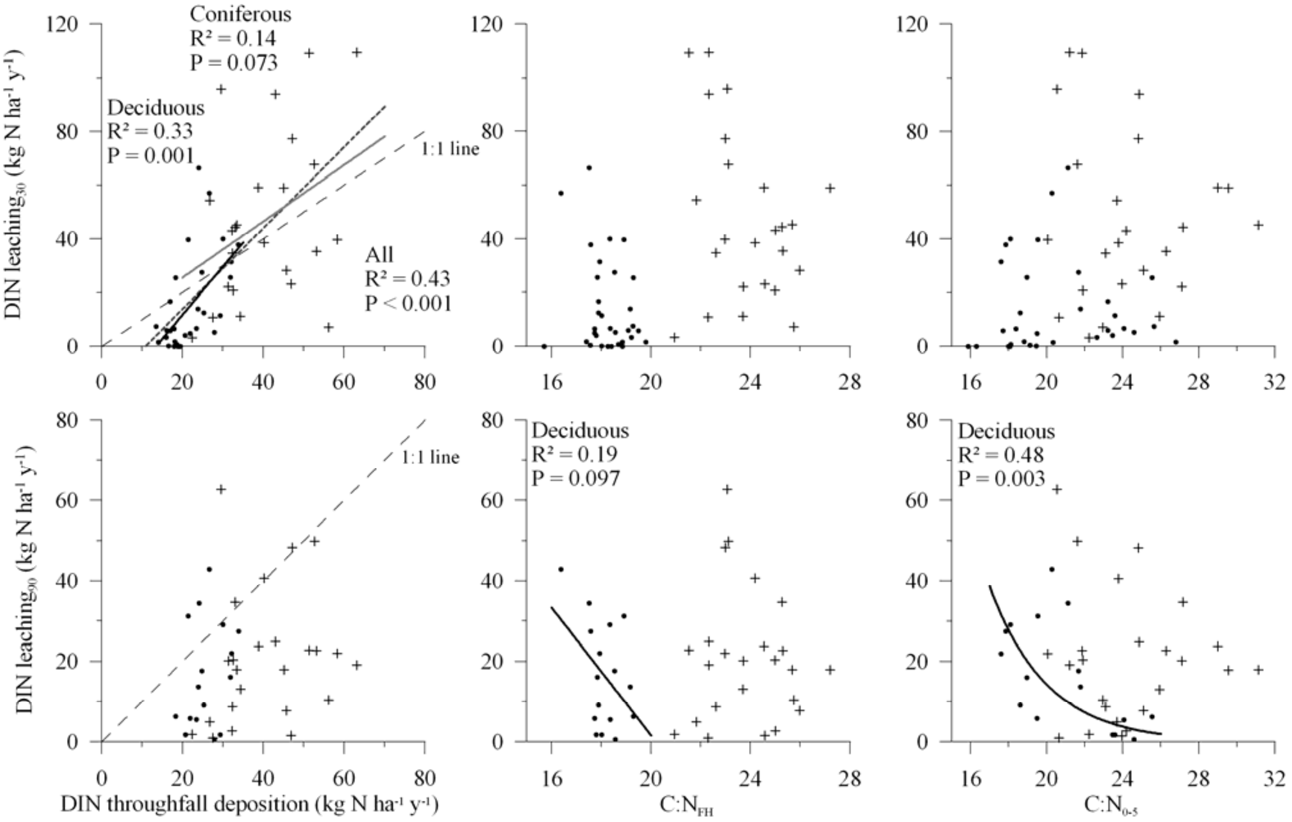
Coniferous
R² = 0.14
P = 0.073
Deciduous
R² = 0.33
P = 0.001
All
R² = 0.43
P < 0.001
1:1 line
DIN leaching30 (kg N ha-1 y-1)
120
80
40
0
0
20
40
60
80
16
20
24
28
16
20
24
28
32
DIN leaching90 (kg N ha-1 y-1)
1:1 line
Deciduous
R² = 0.19
P = 0.097
Deciduous
R² = 0.48
P = 0.003
60
20
DIN throughfall deposition (kg N ha-1 y-1)
C:NFH
C:N0-5

Fig. 3

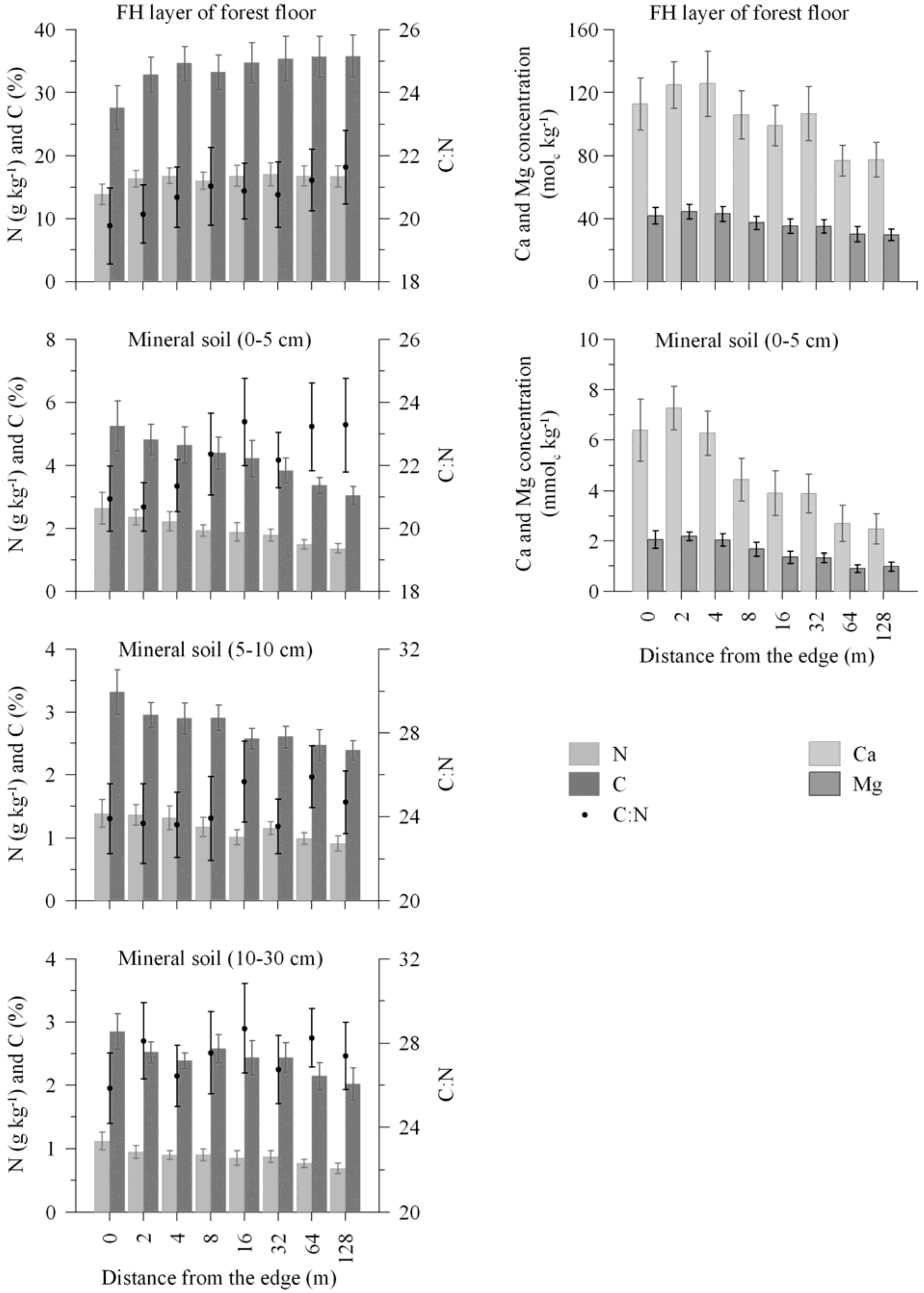
FH layer of forest floor
N (g kg-1) and C (%)
C:N
0
10
20
30
40
18
20
22
24
26
FH layer of forest floor
Ca and Mg concentration (molc kg-1)
0
40
80
120
160
Mineral soil (0-5 cm)
N (g kg-1) and C (%)
C:N
0
2
4
6
8
18
20
22
24
26
Mineral soil (0-5 cm)
Ca and Mg concentration (mmolc kg-1)
0
2
4
6
8
10
Mineral soil (5-10 cm)
N (g kg-1) and C (%)
C:N
0
1
2
3
4
20
24
28
32
Mineral soil (10-30 cm)
N (g kg-1) and C (%)
C:N
0
1
2
3
4
20
24
28
32
0
2
4
8
16
32
64
128
Distance from the edge (m)
N
C
C:N
Ca
Mg

Fig.4