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The importance of forest type when incorporating forest edge deposition in the evaluation of critical load exceedance

Wuyts K, De Schrijver A, Verheyen K

This paper provides an assessment of the effect of incorporating edge deposition in the evaluation of critical load exceedance in forests, taking into account pollutant type, meteorological conditions, edge orientation, and forest type. In particular we have calculated critical load exceedance in five Flemish regions differing in forest fragmentation extent and/or share of coniferous forest.

Keywords: Forest edge, Edge effect, Exceedance of critical load, Forest type, Fragmentation

Introduction

As the extent of forest fragmentation increases worldwide, forest edges are becoming an increasingly important feature in the landscape matrix (Harper et al. 2005). At forest edges, acidifying (N+S) and nitrogen (N) throughfall deposition are increased up to four times compared to the forest interior, and this edge effect decreases exponentially with increasing distance from the edge (Beier & Gundersen 1989, Draaijers et al. 1994, Spangenberg & Kölling 2004, see De Schrijver et al. 2007 for an overview). Despite their importance, edges are rarely taken into account in the assessment of critical load (CL) exceedance in forest ecosystems, but see Lövblad et al. (1995). De Schrijver et al. (2007) quantified edge impact on critical load exceedance in Flanders, but only provided a rough insight in the error on current calculations, partly because a fixed edge effect was assumed. Yet, the magnitude (*i.e.*, the level of deposition enhancement) and depth of edge influence depend on pollutant type, meteorological conditions, edge orientation, and edge structure (like forest type, edge shape, and leaf area index - Draaijers et al. 1994, Wuyts et al. 2008a, Wuyts et al. 2008b).

The study's aims were to asses: (i) the effect of incorporating edge deposition in the evaluation of CL exceedance in forests, taking into account pollutant type, meteorological conditions, edge orientation, and forest type; and (ii) the importance of forest type in this effect. Therefore, we calculated CL exceedance in five Flemish regions differing in forest fragmentation extent and/or share of coniferous forest.

Laboratory of Forestry, Department of Forest and Water Management, Faculty of Bioscience Engineering, Ghent University. Geraardsbergsesteenweg 267, B-9090 Gontrode-Melle, Belgium.

@ Karen Wuyts
(Karen.Wuyts@UGent.be)

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Summary of methods

In our calculations, we used data on SO_4^{2-}, NO_3^-, and NH_4^+ throughfall deposition along transects perpendicular to the abrupt edges of different forest types, from two field studies performed by Wuyts et al. (Wuyts et al. 2008b, Wuyts et al. 2009) in 2005-2006 and 2006-2007 (Tab. 1 - see Wuyts et al. 2008b for a full description of methods). Integrated Forest Edge Enhancement (IFEE) factors (Tab. 1), which account for both the depth and magnitude of edge effects (DEI and MEI), were computed as the ratio of the throughfall flux that actually reaches the forest floor in the first 64 m of the edge to the throughfall flux that would reach the same area in the absence of edge effects (Wuyts et al. 2008b). Next, by means of meteorological data from the nearest weather stations of the Royal Meteorological Institute of Belgium, the forest edge exposure was determined, which we defined as the proportion of time a forest edge is exposed to wind oriented perpendicular (± 45°) to the edge (in %). Based on year-round wind direction data and the linear relationship between the IFEE factor and the edge exposure (Wuyts et al. 2008a), we derived for each of the edges hypothetical IFEE factors for SO_4^{2-}, NO_3^-, and NH_4^+ for the four principal wind directions. We assumed that no considerable edge effects occur at the lee side of a forest (Pahl 2000). Subsequently, tree species specific, year-round forest interior throughfall deposition was derived from (i) the forest interior plots of the stands and (ii) five Level II plots of the UNEP/UN-ECE Program for the year 2003 (Genouw et al. 2004).

Using ArcView 3.1 (ESRI 2004) and the digital forest cover map "Bosreferentielaag" (Aminal Afdeling Bos en Groen 2001), the total forest area and forest edge area (forest located within 64 m of an open area-to-forest

Tab. 1 - Dominant tree species, location, and edge orientation of the nine selected forest stands and the IFEE factors for the potentially acidifying and eutrophying ions SO_4^{2-}, NO_3^-, and NH_4^+. Data on the forest stands indicated by (1) and (2) have previously been published in Wuyts et al. (2008b) and Wuyts et al. (2009).

Dominant tree species	Region	Edge orientation	IFEE		
			SO_4^{2-}	NO_3^-	NH_4^+
Quercus robur L.[1]	SW-Flanders	SW	1.02	1.07	1.03
Quercus robur L.[1]	NE-Flanders	S	1.08	1.12	1.08
Betula pendula Roth.[1]	W-Flanders	SW	1.18	1.10	1.14
Betula pendula Roth.[1]	NE-Flanders	SW	1.11	1.07	1.06
Pinus nigra ssp. *nigra* var. *nigra* Arnold[1]	W-Flanders	SW	1.45	1.56	1.40
Pinus nigra ssp. *laricio* Maire[1]	NE-Flanders	SW	1.40	1.31	1.26
Quercus robur L.[2]	NE-Flanders	W	1.28	1.14	1.15
Fagus sylvatica L.[2]	S-Flanders	S	1.07	1.08	1.02
Pinus sylvestris L.[2]	S-Netherlands	S	1.42	1.32	1.47

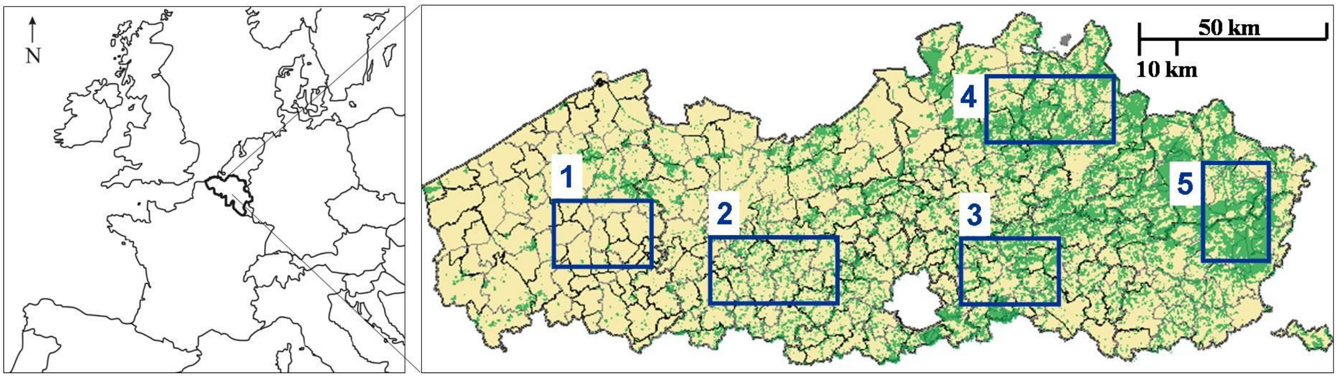


Fig. 1 - Location of the five regions considered in our study. Map of Europe and forest cover map of Flanders (the northern part of Belgium), indicating the five regions for which we calculated critical load exceedance in forest ecosystems (forest cover map of Flanders - Geo-Vlaanderen AGIV 2008).

interface) were determined for five regions of Flanders (northern part of Belgium - Fig. 1) and for all main tree species.

Finally, we computed the total throughfall deposition flux (TF_{total}, eq ha^{-1} yr^{-1}) of SO_4^{2-}, NO_3^-, and NH_4^+ in the entire forest area of the five regions (eqn. 1):

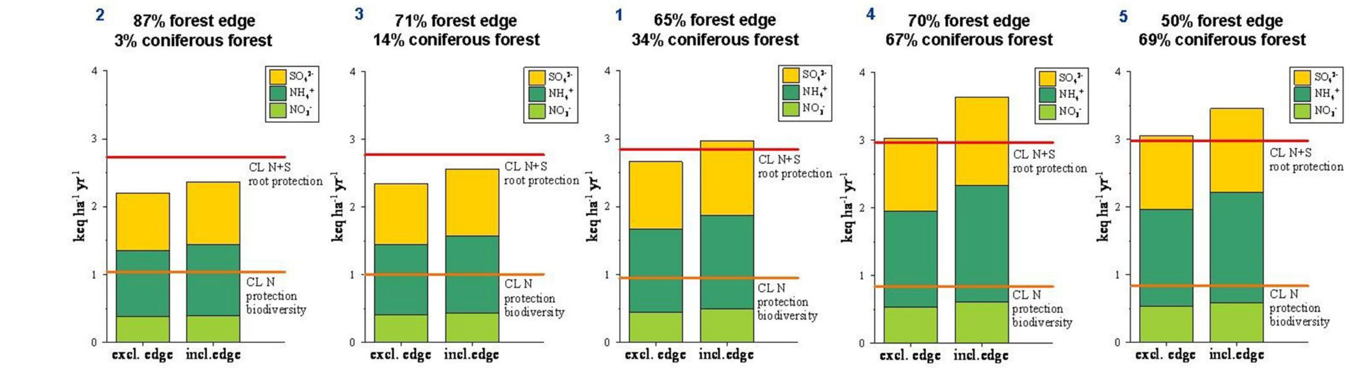
$$K_i = IFEE_{N,i} + IFEE_{E,i} + IFEE_{S,i} + IFEE_{W,i}$$
$$FI_i = area_{FI,i} \cdot TF_{FI,i}$$
$$FE_i = area_{FE,i} \cdot TF_{FE,i}$$
$$TF_{total} = \sum_{i=1}^{s} \left(FI_i + FE_i \cdot \frac{1}{4} \cdot K_i \right) \cdot area_T^{-1}$$

with s the total amount of tree species classes in the forest cover map, $area_{FI,i}$ the forest interior area for species i, $area_{FE,i}$ the forest edge area for species i, $area_T$ the total forest area, $TF_{FI,i}$ the throughfall deposition in the forest interior for species i, and $IFEE_{x,i}$ the integrated forest edge enhancement factor for edges exposed to direction x and for species i. We assumed edge orientation to be equally distributed over all wind directions because sufficiently large areas were considered (480-640 km²). In addition, the total throughfall deposition fluxes of SO_4^{2-}, NO_3^-, and NH_4^+ in the entire forest area of the five regions were determined without accounting for edge effects. These deposition fluxes were summed in N throughfall deposition (NO_3^- + NH_4^+) and acidifying throughfall deposition (SO_4^{2-} + NO_3^- + NH_4^+). Because no interior throughfall deposition and edge effect data were available for poplar (*Populus* sp.), Norway spruce (*Picea abies* L.), and larch (*Larix* sp.), average throughfall deposition and IFEE factors of deciduous or coniferous plots were applied for these species.

In each of the five regions, critical load values for protection of biodiversity and for root protection for deciduous and coniferous forests (Langouche et al. 2001) were averaged by the deciduous and coniferous proportion in the total forest area, this to determine the total CL for the entire forest area. Finally, we calculated the average CL exceedances for each region as the average values of CL exceedances for all stands in the region considered.

Results and discussion

The nitrogen CL for protection of biodiversity was exceeded in all regions, irrespective of taking into account edge effects (Fig. 2). However, when only forest interior deposition was considered, the average exceedance of this CL was 18-26 % lower than when edge deposition was accounted for. At the level of the entire forest area, the CL for acidification was not exceeded in regions 2 and 3, even when the edge deposition was taken into account, while in regions 4 and 5, the CL was exceeded even when ignoring forest edge deposition. In region 1, the acidification CL was exceeded when edge deposition was taken into account, but not when



average CL exceedance

CL N+S	11	37	49	161	126	350	237	793	248	611
CL N	309	397	445	570	727	920	1104	1487	1135	1388

Fig. 2 - The throughfall deposition of SO_4^{2-}, NO_3^-, and NH_4^+ (keq ha^{-1} yr^{-1}) for the entire forest area in the five regions, with and without taking into account forest edge effects (indicated by "incl. edge" and "excl. edge", respectively). The red line represents the total critical load for acidification (root protection); the orange line stands for the total critical load for nitrogen (protection of biodiversity). The number above each chart refers to the corresponding region as indicated in Fig. 1. Below, the average exceedance of the two critical loads are indicated, with and without taking into account edge effects (eq ha^{-1} yr^{-1}).

edge effects were ignored. Despite these differences between the regions when considering the entire forest area, the average exceedance of the CL for acidification was underestimated to the same extent in all regions when edge effects were neglected, *i.e.*, by 60-71 %. So, although Lövblad et al. (1995) found the importance of edge deposition in the CL exceedance in Sweden to be small, our results point to significant underestimations of CL exceedance in Flanders, probably due to differences in forest fragmentation extents. The impact of edge deposition on the exceedance of the same nitrogen CL's was smaller in our study than estimated by De Schrijver et al. (2007). Firstly, in their study, the exponential decrease of deposition in the forest edge zone was not considered (Draaijers et al. 1994); instead, a fixed deposition enhancement in the forest edge zone was assumed, set to the level of deposition enhancement at the outer edge, where the greatest enhancement occurs. Secondly, a median value of deposition enhancement was used generated from more than twenty studies that all but four focused on coniferous forests, which are subject to greater edge effects on deposition. Thirdly, they applied this deposition enhancement also to the stem flow deposition, increasing the absolute effect of edge deposition on CL exceedance.

From regions 1, 3, and 4, characterized by a similar amount of forest edge area in the total forest area (about 70 %), we can infer that the impact of edge deposition on CL exceedance increases in absolute numbers with increasing proportion of coniferous forests (from 112 to 556 eq ha^{-1} yr^{-1} for CL N+S and from 125 to 383 eq ha^{-1} yr^{-1} for CL N - Fig. 2). The impact of edge deposition on total throughfall deposition and CL exceedance was smaller in regions 2 and 3 than in region 5, whereas forests were much more fragmented in regions 2 and 3 than in region 5 (Fig. 2). This was a result of the higher proportion of coniferous forest types in region 5 than in regions 2 and 3. The comparison of region 2 with region 3 (Fig. 2) shows that the effect of a higher forest edge area (by 16%) was surpassed by the effect of a lower coniferous forest fraction (by 11%). These results indicate that forest type, and more specific the share of coniferous forests in the total forest area, has a significant influence on the impact of edge deposition on the exceedance of CLs. This is a result of the greater magnitude and/or penetration depth of the edge effects on throughfall deposition in coniferous stands than in deciduous stands (Wuyts et al. 2008a, Wuyts et al. 2008b).

Although our calculations are not exact assessments of CL exceedance because several assumptions were made and confounding effects of internal edges, stand height, and stand density were not considered, we highlight that measures to reduce atmospheric deposition based on deposition in the forest interior will not be enough to counteract negative effects. In fact, emission reductions should be adjusted to the higher deposition values in the forest edge. Particularly in highly fragmented regions with dominance of coniferous forests, this is a topic of high relevance.

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