

Edge influence on understorey plant communities depends on forest management

Sanne Govaert¹  | Camille Meeussen¹  | Thomas Vanneste¹  | Kurt Bollmann²  | Jörg Brunet³  | Sara A. O. Cousins⁴  | Martin Diekmann⁵  | Bente J. Graae⁶  | Per-Ola Hedwall³  | Thilo Heinken⁷  | Giovanni Iacopetti⁸ | Jonathan Lenoir⁹  | Sigrid Lindmo⁷ | Anna Orczewska¹⁰ | Michael P. Perring^{1,11}  | Quentin Ponette¹²  | Jan Plue⁴ | Federico Selvi⁸  | Fabien Spicher⁹  | Matteo Tolosano^{1,13} | Pieter Vermeir¹⁴ | Florian Zellweger^{2,15}  | Kris Verheyen¹  | Pieter Vangansbeke¹  | Pieter De Frenne¹ 

¹Forest & Nature Lab, Department of Environment, Faculty of Bioscience Engineering, Ghent University, Gontrode-Melle, Belgium

²Swiss Federal Institute for Forest, Snow & Landscape Research WSL, Birmensdorf, Switzerland

³Southern Sweden Research Centre, Swedish University of Agricultural Sciences, Alnarp, Sweden

⁴Biogeography and Geomatics, Department of Physical Geography, Stockholm University, Stockholm, Sweden

⁵Vegetation Ecology and Conservation Biology, Institute of Ecology, FB2, University of Bremen, Bremen, Germany

⁶Department of Biology, Norwegian University of Science and Technology, Trondheim, Norway

⁷General Botany, Institute of Biochemistry and Biology, University of Potsdam, Germany

⁸Department of Agriculture, Food, Environment and Forestry, University of Florence, Florence, Italy

⁹Unité de Recherche «Ecologie et Dynamique des Systèmes Anthropisés» (EDYSAN, UMR 7058 CNRS-UPJV), Université de Picardie Jules Verne, Amiens, France

¹⁰Faculty of Biology and Environmental Protection, University of Silesia, Katowice, Poland

¹¹School of Biological Sciences, The University of Western Australia, Crawley, Australia

¹²Earth and Life Institute, Université catholique de Louvain, Louvain-la-Neuve, Belgium

Abstract

Questions: Does the influence of forest edges on plant species richness and composition depend on forest management? Do forest specialists and generalists show contrasting patterns?

Location: Mesic, deciduous forests across Europe.

Methods: Vegetation surveys were performed in forests with three management types (unthinned, thinned 5–10 years ago and recently thinned) along a macroclimatic gradient from Italy to Norway. In each of 45 forests, we established five vegetation plots along a south-facing edge-to-interior gradient ($n = 225$). Forest specialist, generalist and total species richness, as well as evenness and proportion of specialists, were tested as a function of the management type and distance to the edge while accounting for several environmental variables (e.g. landscape composition and soil characteristics). Magnitude and distance of edge influence were estimated for species richness per management type.

Results: Greatest total species richness was found in thinned forests. Edge influence on generalist plant species richness was contingent on the management type, with the smallest decrease in species richness from the edge-to-interior in unthinned forests. In addition, generalist richness increased with the proportion of forests in the surrounding landscape and decreased in forests dominated by tree species that cast more shade. Forest specialist species richness, however, was not affected by management type or distance to the edge, and only increased with pH and increasing proportion of forests in the landscape.

Conclusions: Forest thinning affects the plant community composition along edge-to-interior transects of European forests, with richness of forest specialists and generalists responding differently. Therefore, future studies should take the forest management into account when interpreting edge-to-interior because both modify

¹³Stream Biofilm and Ecosystem Research Laboratory, School of Architecture, Civil and Environmental Engineering, École Polytechnique Fédérale de Lausanne, Lausanne, Switzerland

¹⁴Laboratory for Chemical Analysis (LCA), Department of Green Chemistry and Technology, Faculty of Bioscience Engineering, Ghent University, Ghent, Belgium

¹⁵Forest Ecology and Conservation Group, Department of Plant Sciences, University of Cambridge, Cambridge, UK

Correspondence

Sanne Govaert, Forest & Nature Lab, Department of Environment, Faculty of Bioscience Engineering, Ghent University, Gontrode-Melle, Belgium.
Email: Sanne.Govaert@UGent.be

Funding information

This work was supported by the Research Foundation Flanders (FWO) (project GOH1517N), and the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (ERC Starting Grant FORMICA 757833) and ERC Consolidator Grant (PASTFORWARD 614839). The FWO Scientific research network FLEUR (www.fleur.ugent.be) also supported this work.

Co-ordinating Editor: Kerry Woods

[Correction added on 27 February 2020, after the first online publication: the affiliation of Jonathan Lenoir and Fabien Spicher has been corrected.]

the microclimate, soil processes and deposition of polluting aerosols. This interaction is key to predict the effects of global change on forest plants in landscapes characterized by the mosaic of forest patches and agricultural land that is typical for Europe.

KEYWORDS

edge effects, edge influence, forest specialists, generalists, herbaceous layer, patch contrast, plant biodiversity, species richness, thinning, understorey

1 | INTRODUCTION

Forests harbour more than two-thirds of terrestrial biodiversity (Millennium Ecosystem Assessment, 2005). In Europe, dramatic deforestation in the past has led to habitat loss and fragmentation, both being major drivers of biodiversity loss (Secretariat of the Convention on Biological Diversity (CBD), 2010). Habitat fragmentation creates new forest edges and subsequently leads to a higher edge-to-interior ratio (Saunders, Hobbs, & Margules, 1991). At least 20% of the world's forest area lies within 100 m of a forest edge (Haddad et al., 2015), indicating the need to further our understanding of how edges affect forest biodiversity and functioning. Compared with forest interiors, forest edges experience more solar radiation, higher wind speeds and faster air mixing, resulting in higher light availability, decreased soil moisture, higher maximum and lower minimum temperatures, and increased diurnal and seasonal variability in temperatures (Chen et al., 1999; Gehlhausen, Schwartz, & Augspurger, 2000; Matlack, 1993; Schmidt, Lischeid, & Nendel, 2019; Tuff, Tuff, & Davies, 2016). In addition to altered microclimatic conditions, forest edges, as opposed to forest interiors, are also characterized by

a higher seed influx of non-forest species (Devlaeminck, Bossuyt, & Hermy, 2005), differences in disturbance regimes, and higher nitrogen (N) and carbon (C) stocks (Remy et al., 2016). These biotic and abiotic factors all influence understorey plant communities, which contain more than 80% of total plant species' richness in temperate forests and are essential for several ecosystem functions such as nutrient cycling, carbon dynamics and tree regeneration (Gilliam, 2007; Landuyt et al., 2019; Whigham, 2004).

In general, higher understorey species richness occurs at forest edges because those environmental conditions are intermediate between the forest interior and the matrix. However, not all species respond similarly, and species can be grouped according to their ecological preferences (Gehlhausen et al., 2000; Guirado, Pino, & Rodà, 2006; Murcia, 1995). For example, a study in temperate forests in northern France found that edge species were more often thermophilous (warmth-loving), basophilous (alkaline-loving), nitrogen- and light-demanding, and species reproducing by seed only (and not clonally; Pellissier et al., 2013). In contrast, interior species were more often slow-colonizing species, acidophilous and reproducing both by seeds and vegetatively (Pellissier et al., 2013). The effect of distance to edge,

hereafter also referred to as 'edge influence', on species richness has been related to mechanisms such as past land-use change (Berges et al., 2016), changes in light regime (Honnay, Verheyen, & Hermy, 2002) and altered soil moisture content (Gehlhausen et al., 2000).

While edge influence has been well studied in dense forests in single regions or landscapes, less is known about how edge influence interacts with forest management across forest types in Europe. Similar to habitat fragmentation, forest management also affects forest microclimate, and thus light availability, temperature, soil moisture and nutrient availability (Ash & Barkham, 1976; Grayson et al., 2012). Understorey plant communities respond to changes in light and soil disturbances, which can be induced by forest management practices (Ash & Barkham, 1976; Aude & Lawesson, 1998; Decocq et al., 2004; Scolastri, Cancellieri, Iocchi, & Cutini, 2017; Strubelt, Diekmann, Griese, & Zacharias, 2019; Widenfalk & Weslien, 2009). It can be expected that forest management, which influences the overall forest structure and edge physiognomy, interacts with edge influence on understorey species richness and composition by reducing the edge contrast with the surrounding matrix (Cadenasso & Pickett, 2001; Harper et al., 2005; Ries, Fletcher, Battin, & Sisk, 2004). For example, open, thinned forests might be more susceptible to the penetration of wind and seeds into the forest interior owing to lower edge contrast. Moreover, energy exchange in open forests is also determined by the lower albedo of dark surfaces in the understorey, such as the soil surface, litter and tree trunks, instead of the green leaves of the canopy cover (Wright, Kasel, Tausz, & Bennett, 2010).

Here, we studied understorey vegetation biodiversity and composition responses to distance to the forest edge in ancient forest stands (i.e. continuously forested since the first available land-use maps and thus never converted to another land-use type) with different management types (unthinned, thinned and recently thinned) in 45 edge-to-interior forest transects across Europe. Our aim was to disentangle the effects of the management type and the distance to the edge on alpha diversity of understorey plants in multiple European regions, while accounting for environmental characteristics. We expected to find (a) higher species richness at edges, with forest specialists and generalists responding differently to management intensity and (b) interactions between distance-to-edge influence and forest management on richness. For example, the edge-to-interior gradient is expected to become weaker in increasingly managed (thinned) forests and thus have less impact on understorey plant diversity than in recently thinned forests.

2 | MATERIALS AND METHODS

2.1 | Study region and set up

Our study area included the temperate, Mediterranean and boreonemoral forest biomes of Europe. We focused on deciduous broad-leaved forests, which are hotspots of biodiversity and a widespread and ecologically important forest type in most of Europe (Brus et al., 2012). Study sites are situated in typical European fragmented

landscapes, with forest patches surrounded by a matrix of arable fields and grasslands. Forest stands were selected across nine regions along a latitudinal gradient from Italy to Norway to capture as much of the macroclimatic variation across Europe as possible (Figure 1a). In the south, middle and north of this latitudinal gradient, more specifically in Italy, Belgium and Norway, an elevational gradient with three levels (low, medium and high) was included to capture macroclimatic variation caused by elevation. Study sites of the elevational gradient were selected to have a similar understorey composition to that of the lowlands of the same region (with understorey plant species typical for Natura2000 habitat types 9120 and 9130). A total of 15 sites were thus selected: six regions without an elevational gradient and three regions with three levels of elevation (Figure 1). A study site description can be found in Appendix S1.

Forest stands were selected in a standardized way to increase the comparability of sites. The stands, with a minimum forest area of 1 ha, were deciduous and mainly dominated by oaks (*Quercus robur*, *Quercus petraea*, and *Quercus cerris*), *Fagus sylvatica*, *Betula pubescens*, *Populus tremula*, *Ulmus glabra*, *Alnus incana* and *Carpinus betulus*. All sites had the same type of land-use history (ancient forest) and intermediate soil moisture (mesic).

At each site, three forest stands with different forest management were selected: unthinned (1), thinned (2) and recently thinned (3) (Figure 1b; see Appendix S2: site selection protocol).

1. The first type (unthinned) is typically a dense forest, with a well-developed shrub layer, high basal area (mean \pm SE was here 28.8 ± 1.5 m²/ha) and high canopy cover (openness $5.8 \pm 0.6\%$, mean of three densitometer measurements, Appendix S3), and not thinned for at least 10 years and mostly >30 years ago, indicated by, for example, the absence of cut tree stumps.
2. The second type is intermediate to types one and three (openness $6.5 \pm 0.6\%$, basal area 31.4 ± 1.9 m²/ha; Appendix S3); even-aged and regularly thinned, but not recently (probably 5–10 years ago).
3. The third type is typically an open, even-aged and recently thinned forest (probably within 4 years of sampling), indicated by the presence of cut tree stumps, and characterized by the absence of a shrub and subdominant tree layer, with low basal area (21.6 ± 1.3 m²/ha) and low canopy cover (mean openness $14.8 \pm 2.1\%$; Appendix S3).

We established 100 m transects from the southern forest edge to the forest interior of each forest stand at each site. We thus established 45 transects in total (15 sites \times 3 management types). The transect started at the hypothetical line of tree stems at the edge of the forest stand (0 m). These edges are outer edges, bordering a matrix of agricultural land and were created by ancient deforestations (Appendix S1). Because edge orientation affects understorey species richness and microclimatic conditions (Didham & Lawton, 1999; Honnay et al., 2002; Matlack, 1993; Orczewska & Glista, 2005), we standardized this by only locating the transects at the south-facing edge (or south-western or south-eastern), bordering with either grassland or arable land (Appendix S1). The transect was installed perpendicular to the edge

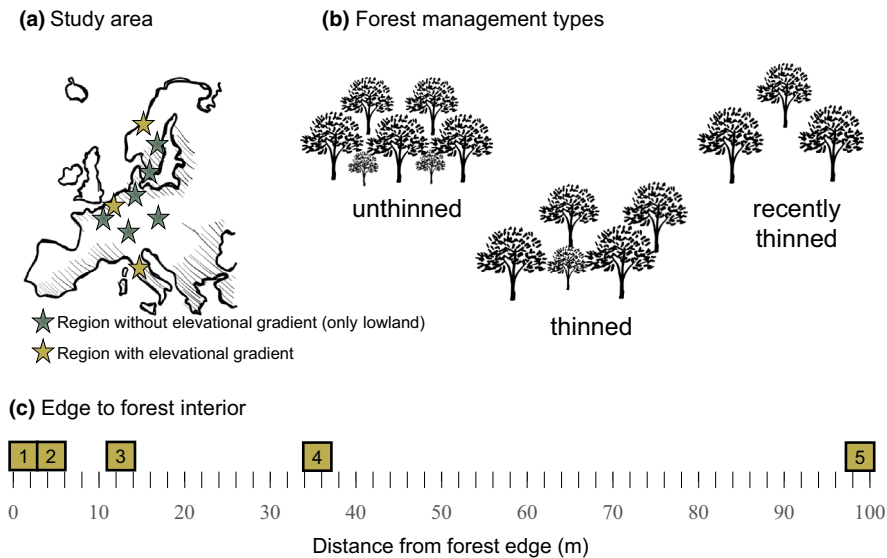


FIGURE 1 Study set up. Nine regions were selected across a latitudinal gradient in Europe (a). To study the effect of forest management, we compared unthinned, thinned and recently thinned forests (b). Study plots were distributed with an exponentially increasing distance from the south-facing forest edge to the interior (c) [Colour figure can be viewed at wileyonlinelibrary.com]

and at least 100 m from any another edge. Elements that affect the microclimate at the edge or along the transect (such as water bodies, buildings and wide, tarmacked roads) were avoided.

Along each transect, five $3 \times 3 \text{ m}^2$ quadrats were installed at an exponentially increasing distance from the forest edge because of the exponential change in microclimatic condition close to the edge (Chen et al., 1999; Didham & Lawton, 1999), resulting in a total of 225 plots. The centres of the plots were thus at distances of 1.5, 4.5, 12.5, 35.5 and 99.5 m from the edge (Figure 1c). However, in six plots the centres were located at different distances (for example at 18 m instead of 12.5 m) to avoid the influence of forest paths on the vegetation.

2.2 | Plant biodiversity variables: understorey

Vegetation surveys were conducted at the peak of vegetation biomass from May until early July 2018, depending on the regional phenology (Appendix S1). All vascular plant species were identified and their percentage ground cover visually estimated by teams of two persons. The herb layer included all vascular species, both woody plants smaller than 1 m and non-woody plants, as well as lianas. The shrub layer was defined as all woody species with a height between 1 and 7 m and the tree layer as all trees reaching heights more than 7 m. *Corylus avellana* was always classified into the shrub layer, regardless of its height. Species nomenclature follows Euro+Med (2006).

Plant species of the herb layer were assigned to five forest guilds following Heinken et al. (2019): species that can be mainly found in the closed forest (1.1); species that occur typically along forest edges and in forest openings (1.2); species that can be found in both forest and open vegetation (2.1); species that can be found partly in forest, mainly in open vegetation (2.2); and true open habitat species (O) (Appendix S4). In our data set, few species belonged to forest guilds 1.2, 2.2 and O (with 70%, 45% and 86% of the plots containing zero species of these guilds, respectively), and therefore all species belonging to 1.1 and 1.2 were grouped as forest specialists and those

belonging to 2.1, 2.2 and O as generalists. Hereinafter, forest guild 1.2 will be referred to as closed forest species. According to Heinken et al. (2019) species can shift forest guilds over the geographical gradient: thus the forest guild a certain species was assigned was dependent on the region it was observed in. Individuals determined only to the genus level were excluded from this categorization, as well as seven species (out of 383 taxa) for which no data was available to classify them as forest specialists or generalists (Appendix S4).

2.3 | Environmental predictor variables

Light transmission differences resulting from overstorey species identity were accounted for by means of the shade casting ability (SCA) index. The SCA index is a species-specific, expert-based index that varies from 1 to 5, indicating low to high shade casting ability of the canopy species (Verheyen et al., 2012). The SCA of the canopy (the shrub and tree layer combined) was calculated as a cover weighted mean of the scores listed in Appendix S5.

In all 225 plots, topsoil samples (0–10 cm depth, diameter 30 mm) were collected for chemical analyses (pH and soil nutrient concentration) and between 10–20 cm depth for texture analysis (% silt, clay and sand). Within each plot, five random subsamples were taken after removal of the litter layer and pooled together. The 0–10 cm soil samples were dried to constant weight at 40°C for 48 h, ground and sieved over a 2 mm mesh. These samples were analysed for pH-H₂O by shaking a 1:5 ratio soil/H₂O mixture for 5 min at 300 r.p.m. and measuring with an Orion 920A pH meter with a Ross sure-flow 8172 BNWP pH electrode model (Thermo Scientific Orion, USA). To measure the total concentration of C and N in the soil, subsamples were combusted at 1,200°C and the gases were measured by a thermal conductivity detector in a CNS elemental analyser (vario Macro Cube, Elementar, Germany). Bioavailable phosphorus (P) which is available for plants within one growing season (Gilbert, Gowing, & Wallace, 2009) was measured by extraction in NaHCO₃ (P_{Olsen}; according to ISO, 11263,

1994) and colorimetric measurement according to the malachite green procedure (Lajtha, Driscoll, Jarrell, & Elliott, 1999). Total calcium (Ca), potassium (K) and magnesium (Mg) were measured by atomic absorption spectrophotometry (AA240FS, Fast Sequential AAS) after complete destruction of the soil samples with HClO_4 (65%), HNO_3 (70%) and H_2SO_4 (98%) in Teflon bombs for 4 h at 150°C. Texture analysis was performed by sieving and sedimentation with a Robinson–Köhn pipette according to ISO 11277 (2009).

Landscape and topographic characteristics were derived from satellite-based global tree cover data with a spatial resolution of 30 m (Hansen et al., 2013) and a pan-European digital elevation model (DEM) with a spatial resolution of 25 m, using Copernicus data and information from the European Union (EU-DEM, 2018). The proportion of forest cover, hereafter proportion forest, was assessed within a circular buffer area with a radius of 500 m and measured as the percentage of area covered by a minimum tree cover of 20% (Hansen et al., 2013). Forest edge density was computed by transforming the forest cover mask into contour lines and summing their length within the 500 m buffer area using the *rasterToContour* function in the R package *raster* (Hijmans, 2019).

The mean annual temperature (°C) and De Martonne's aridity index were used to take into account macroclimatic variation from latitudinal and elevational differences. De Martonne's aridity index was calculated by dividing the mean annual precipitation (mm) by mean annual temperature plus 10°C (de Martonne, 1926). Temperature and precipitation data were extracted for each plot from the CHELSA database for 1979–2013 (Karger et al., 2017).

2.4 | Data analysis

In total, six response variables were tested comprising measurements for alpha diversity of the understorey layer. The number of forest specialist species (1), as well as generalist richness (2) and total species richness (3) per plot, were calculated. In addition, Pielou's evenness index (4; Pielou, 1966) and the proportion of forest specialists compared with the total number of species (5) were also determined. As two forest guilds (1.1 and 1.2) were grouped as forest specialists, the number of closed forest species (6) was also calculated to allow comparison of the closed forest species and forest specialists.

Two out of 225 plots did not contain any understorey species. These two plots were therefore omitted from the analysis on evenness and proportion of specialists.

To take into account the hierarchical structure of the data, (generalized) linear mixed-effects models were used with transect nested within region as random effect (random intercepts). Poisson error distributions were applied for the count data (such as species richness), while a binomial distribution was used for the proportion of forest specialists. Evenness was initially modelled with a binomial distribution as well, but this models had convergence issues, and therefore a Gaussian error distribution was applied for the model presented here.

Models were built in a two-step process (Perring et al., 2018). First, a model including latitude, elevation (as continuous variables), soil

variables (pH, C:N ratio, % silt, % clay, Olsen-P and K), SCA, the proportion of forest and edge density was assessed for each of the eight response variables. Mg, Ca and sand (%) were highly correlated with other explanatory variables and thus left out of the analysis (Appendix S6). Olsen-P and K were log-transformed to symmetrize the skewed distribution and eradicate influential outliers. For the sake of simplicity, quadratic terms were not included to keep the number of explanatory variables as low as possible. The most parsimonious model (single best model) was selected based on the Akaike Information Criterion (AIC) with the *dredge*-function of the package *MuMIn* (Barton, 2019). Second, the focal explanatory variables, that is, the distance to the edge and the forest management type, were added to the simplified model as a two-way interaction, resulting in the final model. Parallel to these analyses, the same procedure was followed for analyses taking macroclimatic variables into account by replacing latitude and elevation with the mean annual temperature and De Martonne's aridity index.

The distance to the edge was log-transformed to linearize the relationship. The figures presented show the back-transformed results. All continuous explanatory variables were scaled (z-transformation) to facilitate comparisons. A protocol for data exploration and model evaluation was followed precisely (Zuur, Ieno, & Elphick, 2010). All analyses were performed in R (R Core Team, 2018), with packages *lme4* (Bates, Machler, Bolker, & Walker, 2015) and *MuMIn* (Barton, 2019).

In addition, the magnitude of edge influence (MEI) and distance of edge influence (DEI) were calculated per management type for specialists, generalist and total species richness. For each transect, MEI was estimated for the four edge plots as $(e - i)/(e + i)$ where e is the response value at the edge (either at 1.5 m, 4.5 m, 12.5 m or 35.5 m), and i the response value at the forest interior (99.5 m), resulting in four MEI values per transect. We report the mean and standard error of MEI calculated per management type. Next, we calculated the distance at which MEI was significantly different from zero per management type (this is the DEI), by means of a randomization test of edge influence (RTEI) with blocking (Harper & Macdonald, 2011). A routine provided by Dodonov, Harper, and Silva-Matos (2013) was used: (a) For each distance to the edge, the observed MEI was calculated relative to the interior plot (99.5 m). (b) A data set was created with the edge and interior values. (c) One value was randomly assigned to be the new edge value, and the leftover as the interior value. (d) We calculated randomized MEI based on the randomized edge and interior values. (e) Steps 3–4 were repeated 5,000 times for a significance level of 1%, resulting in a distribution of randomized MEI values. (f) Two times the percentile of the observed MEI within the distribution of the randomized MEIs was used as the p -value ($\alpha = 0.01$) for this distance. This routine was repeated per distance to the edge per management type. The DEI was estimated as the farthest distance from the edge that was preceded by no more than one non-significant value (Dodonov et al., 2013).

3 | RESULTS

In total, 351 understorey plant species were identified to the species level, and 32 only to the genus level. Of all species, 97 were forest

specialists across all regions and 224 generalists, while 23 species switched forest guilds across regions (Appendix S4). Recently thinned forest stands were, in general, richer in generalists compared with unthinned forest stands (on average 13.3 and 11.4 species, respectively) (Figure 2). The total number of species as well as the number of generalists decreased from the edge to the interior (Figure 2), but for generalists, this pattern was dependent on the management type: in unthinned forests, no effect of the distance to the edge was detected (Figure 2c). However, in thinned and recently thinned forests, the number of generalist species was highest at the edge and declined exponentially towards to forest interior. Generalist richness decreased more strongly from edge to interior in thinned than in recently thinned forests. In thinned (and recently thinned) forests, on average 8.3 (8.3) generalist species were found at the edge, compared with only 4.5 (5.7) generalist species at the forest interior. Because of the decreasing generalist and stagnant specialist numbers from the edge to interior, the proportion of specialist species increased (Table 1). Neither the distance to the edge nor the management type influenced the number of forest specialists (Figure 2b).

Richness of forest specialists, generalists and total species richness increased with the increasing proportion of forest in a radius of 500 m (Figure 3a). Furthermore, the community-weighted SCA of the tree and shrub layer positively affected the proportion of forest specialists, but negatively affected total species richness and generalist richness (Figure 3c). In contrast, soil pH was positively correlated with the total number of plant species and with the species richness of forest specialist (Figure 3b). Finally, the proportion of forest specialists was the highest when the amount of edge in a radius of 500 m was minimal (Table 1). Evenness increased with percentage silt in the topsoil (Table 1). Analysing the closed forest species richness alone provided the same findings as for specialist richness (Appendix S7). The macroclimatic analysis, with mean annual

temperature and De Martonne's aridity index replacing latitude and elevation, did not differ much from the initial analysis (reported in Appendix S8).

The MEI and DEI results were in line with the outcomes of the previous results. Both MEI and DEI varied across management types and species richness variables (Figure 4). The MEI was greatest in (recently) thinned forests for generalists and total richness, while it was close to zero for forest specialist richness (Figure 4a). The edge influence was not significant for forest specialists in all three management types (Figure 4b). Total species and generalist richness were significantly higher at the first 1.5–4.5 m and 18–35.5 m, respectively, in (recently) thinned forests. In unthinned forests, the MEI was not significantly different from zero for any of the three response variables.

4 | DISCUSSION

Forest management interacted with edge-to-interior gradients on generalist species richness in ancient forests along a latitudinal gradient across Europe. Contrary to our hypothesis, the edge-to-interior gradient in (generalist) species richness was stronger in thinned forests than in unthinned forests, where richness gradients were weaker. Forest edges in unthinned forests were likely more densely vegetated along the entire vertical gradient compared with those in thinned and recently thinned forest. This 'vegetation wall' may thus have served as an effective barrier that buffered the forest interior from seed inflow from the matrix (Devlaeminck et al., 2005), from wind and solar radiation (Honnay et al., 2002; Matlack, 1993), and from influx of warm air thereby preserving the microclimatic conditions typical of the forest interior. In this study, edge sealing might have occurred at the non-forest side of the 0 m edge plot, as the detected MEI was close to zero.

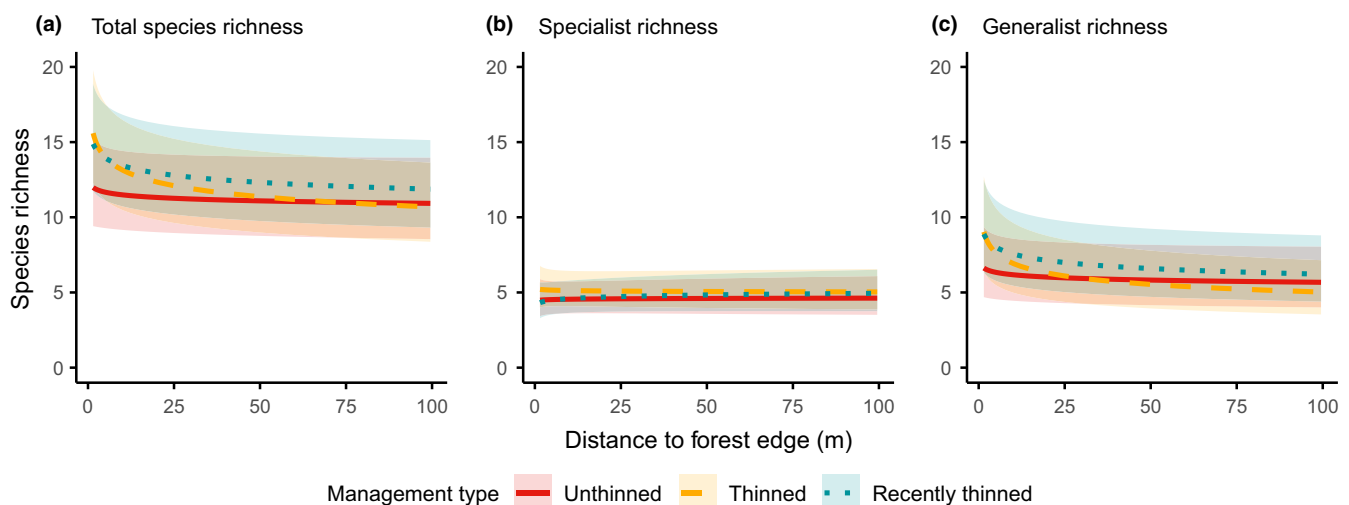


FIGURE 2 Effects of the distance to the forest edge on generalist richness depend on the forest management type. Effects of the distance to the forest edge on species richness (a–c) in forests with different forest management types. The interaction effect is significant at the 0.05 level for total species richness (a), and the main effect of distance to edge is significant for generalist richness (c). Lines represent model estimates of the effects, with other continuous variables set at their observed mean. Shaded areas indicate 95% confidence intervals [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 1 Effects of forest management type, distance to the forest edge, the interaction between the distance to the edge and forest management, the proportion of forest in a radius of 500 m, soil potassium concentration (K), soil pH, SCA (shade casting ability), soil texture (clay and silt percentage), elevation and forest edge density on species richness, evenness and species composition of forests across Europe

	Interaction (management type × distance to edge)				Variation explained			
	Management type	Distance to edge (m)	Proportion forest (%)	Forest edge density (m/ha)	Marginal r^2 (%)	Conditional r^2 (%)		
Total species richness	7.96	27.05***↓	5.91↑	11.99***↓	22	72		
Specialist richness	1.81	0.91	5.14↑	6.55**↑	16	49		
Generalist richness	10.41*	10.41↓	6.06↑	13.68***↓	17	73		
Proportion specialists	7.61	20.09***↑	4.45	7.27**↑	3	7		
Evenness	1.14	2.59	0.91	1.01	7	46		
					5.75*↑			

Environmental variables not shown in the table were not included in any final model (latitude, Mg, P and C:N ratio). Values here are χ^2 of the (generalized) linear mixed models. Symbols denote significance levels ($p < 0.05^*$, $p < 0.01^{**}$, $p < 0.001^{***}$), arrows denote the direction of the continuous effects (positive ↑, negative ↓). The marginal r^2 is the proportion of variance explained by the fixed factors alone, while the conditional r^2 is the proportion of variance explained by both the fixed and random factors.

In recently thinned forests, forest edge and interior microclimates did not contrast much probably owing to more incoming solar radiation in the forest interior, resulting in a more gradual gradient that levels off more quickly in species richness. For example, sparse Mediterranean temperate forests in southern Australia are found to have less pronounced edge influence on the microclimate than in closed forests, with reversed patterns being recorded (e.g. warmer and drier forest interiors compared with edges; Wright et al., 2010). In thinned forests, however, interior and edge conditions were presumably most dissimilar

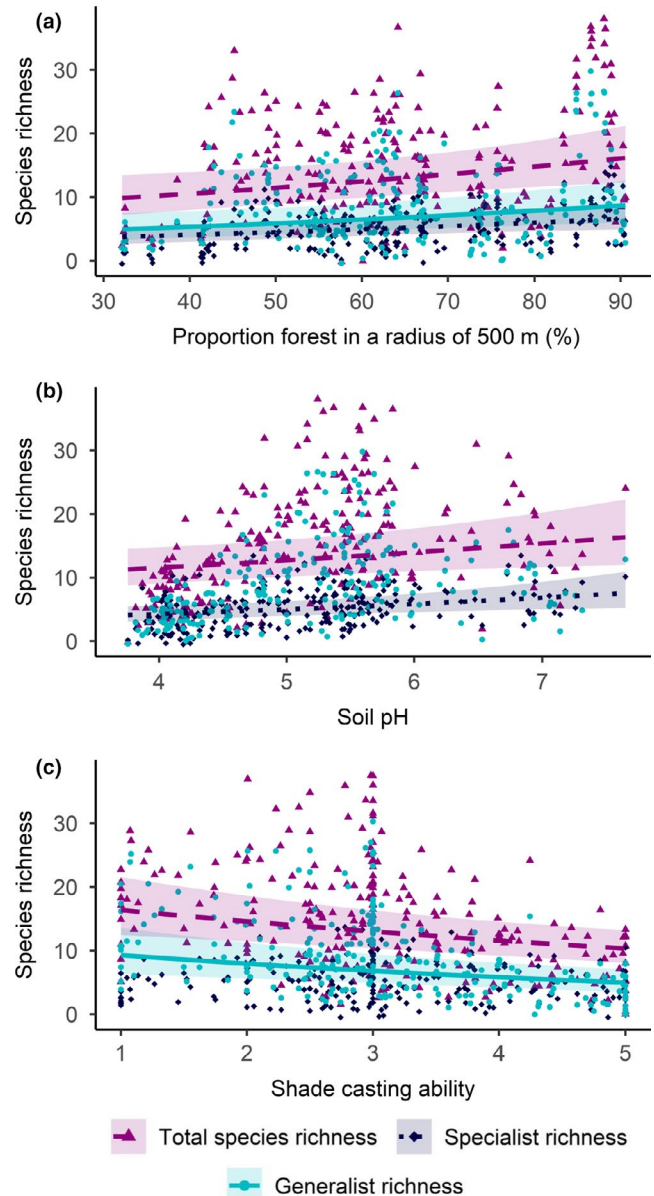


FIGURE 3 Understorey species richness increases with the proportion of forest cover in the landscape (a), soil pH (b) and decreasing shade casting ability (SCA) index of the overstorey (c). Lines represent model estimates with the other continuous variables set at their observed mean and with forest management set to thinned. Shaded areas indicate 95% confidence intervals. A small amount of random variation is added to the location of each point along the y-axis of panel c to avoid overplotting (jittering) [Colour figure can be viewed at wileyonlinelibrary.com]

and edges relatively open, resulting in steep edge-to-core gradients in species richness penetrating 35.5 m into the forest. Hence, forest management modifies the contrast in structure and composition, which in turn determines the magnitude and distance of edge influence (Harper et al., 2005).

Distance to the edge had the most significant effects on species richness. Indeed, the decline of total species richness from the edge to interior corroborates the findings of Fraver (1994), Gehlhausen et al. (2000), Guirado et al. (2006), Honnay et al. (2002), Pellissier et al. (2013), Vallet, Beaujouan, Pithon, Roze, and Daniel (2010) and Willi, Mountford, and Sparks (2005). Greater species richness at forest edges compared with forest interiors was mostly driven by increased generalist richness at the edge, while forest specialists richness was constant along the edge-to-interior transects. Forest specialists thrive best in spatially/temporal varying intermediate light conditions and are characterized by a slow demography (Whigham, 2004), and can thus persist at the edge. At the same time, many generalists can opportunistically colonize edge habitats, which are characterized by increased disturbance regimes (Godefroid & Koedam, 2003), warmer temperatures and a relatively greater amount of available resources, such as light and nutrient inputs (Brunet et al., 2011; Thimonier, Dupouey, & Timbal, 1992). As a result, forest edges were more species-rich compared with interiors in our study (14 and 11 species per plot, respectively, on average), and the proportion of forest specialists was highest in the forest interior, and lowest at the edge. Conversely, some studies also detected decreasing richness from edge to interior for forest specialists, for example, in oak (*Q. robur*) and chestnut (*Castanea sativa*) dominated forests in northern France (Vallet et al., 2010). However, that study was performed at a smaller, regional scale and forests were not selected to be continuously forested since the last available land-use maps. In addition, Guirado et al. (2006) observed higher forest species richness at the edge compared with the interior over a distance of 500 m in oak and pine dominated Mediterranean forests in Spain, indicating that distance-to-edge influence is dependent on the specific condition of the studied system.

Furthermore, forest management also influenced species diversity patterns. Recently thinned forest stands harboured an overall greater generalist diversity compared with thinned and unthinned stands. In contrast, forest specialist as well as total species richness did not consistently differ between the three forest management practices tested. Forest management practices, such as thinning, can indeed strongly modify the understorey environmental conditions by enhancing the amount of solar radiation penetrating the canopy, increasing disturbances and modifying resource availability and microclimatic conditions (e.g. light, temperature, humidity and soil moisture; Ash & Barkham, 1976; Grayson et al., 2012). Changes in the amount of light along with microclimatic stability and soil disturbance are the most important drivers of understorey plant diversity following forest management practices (Ash & Barkham, 1976; Aude & Lawesson, 1998; Brunet, Falkengren-Grerup, & Tyler, 1996; Decocq et al., 2004; Scolastri et al., 2017; Strubelt et al., 2019; Widenfalk & Weslien, 2009), which explains why light-demanding generalists can thrive in thinned, open forests. In contrast, forest specialists can tolerate the changed environmental conditions. Forest specialists often lag behind environmental drivers (Hermy, 2015), requiring them to cope with altered environmental conditions (Decocq et al., 2004) and show extinction debts (Vellend et al., 2006). However, most forest specialists depend on intermediate disturbance for long-term survival.

While we focused on the effects of forest edges, forest management and their interaction, we also took into account environmental variables that potentially influence understorey species richness and composition. The amount of forest in the surrounding landscape was important to predict the number of total species, specialists and generalists. Specialist richness was associated with the forest cover. High forest cover in the landscape may positively influence dispersal and colonization of forest specialists, as obligate forest specialists are poor colonizers (Ehrlén & Eriksson, 2000). What is intriguing is that generalist richness increased similarly with the amount of forest cover in the landscape. This pattern might be associated with

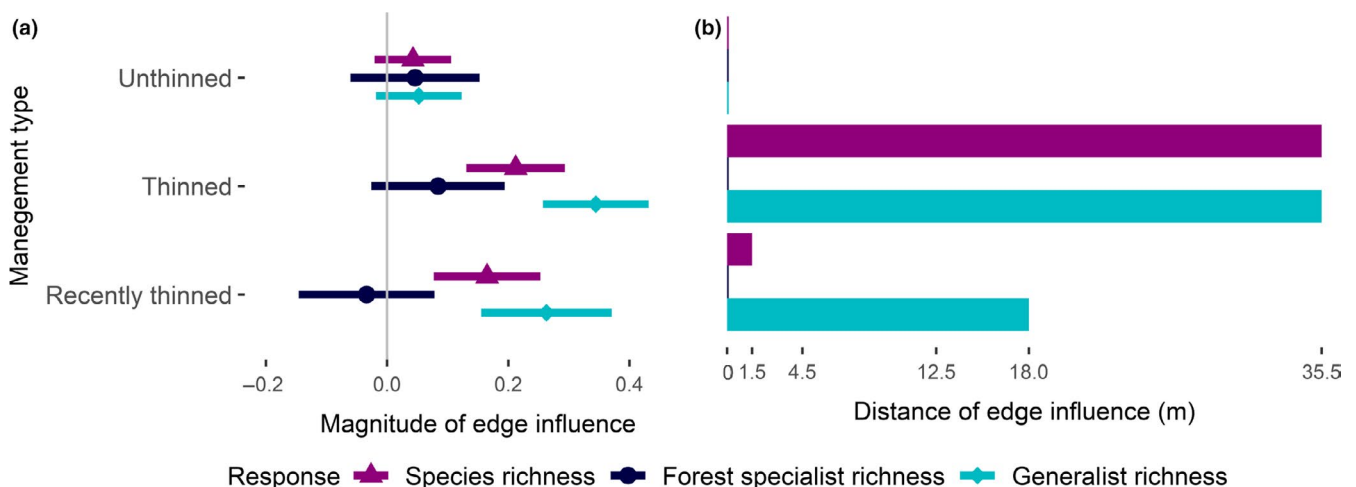


FIGURE 4 Magnitude of edge influence (MEI) (a) and distance of edge influence (DEI) (b) per management type per response variable. In (a) the mean is depicted with error bars indicating 95% confidence intervals [Colour figure can be viewed at wileyonlinelibrary.com]

land-use intensity, as more forest at the landscape level gives an indication about the (semi-)naturalness of the environment, and is likely negatively related to the amount of intensive agriculture and nitrogen input (Jamoneau et al., 2011; Paal, Kuett, Lohmus, & Liira, 2017; Takkis et al., 2018). Alternatively, high forest cover in the surrounding landscape is also linked to a higher availability of forest edges (at least in fragmented landscapes), and thus perhaps to more available habitat for generalists. However, the density of forest edge in the landscape, a measure of fragmentation, did not explain additional variability in generalist richness. The density of forest edges did affect the proportion of forest specialists negatively, although this model explained little variation in response, and the numbers of generalists and specialists were not impacted significantly (Table 1). This indicates that the amount of forest in the landscape has positive effects on understorey species richness, while the density of forest edge in the surrounding landscape is of minor importance.

High community-weighted SCA (shade casting ability), a measure for light transmission differences caused by overstorey composition, resulted in lower total and generalist species richness. Thus, in our study, the greatest species richness was detected in forest stands dominated by *Betula pubescens*, *Quercus robur* and *Populus tremula*, species with relatively low SCA. In contrast, understorey species richness was least under canopies dominated by species with relatively high SCA such as *Fagus sylvatica*, *Carpinus betulus* and *Ulmus glabra*. Shade-intolerant generalists were suppressed by a lack of light, as the proportion of specialist species increased slightly with increasing SCA levels. The composition of the overstorey has been shown to be important to explain compositional shifts in understorey communities, by changing the availability of light (Baeten et al., 2009).

Of all the soil variables measured, only soil pH had a significant influence. Specialist richness increased with increasing soil pH resulting in increasing total species richness, consistent with literature (Borchsenius, Nielsen, & Lawesson, 2004; De Keersmaeker et al., 2004). However, the true relationship between pH and richness of total species and generalists is may be more hump-shaped, with an optimum around pH 5.5 (Figure 3b; Schuster & Diekmann, 2003). Our results are in agreement with Brunet et al. (2011), who found that forest specialists are not affected by light (measured as the tree and shrub cover), but by soil pH, while the opposite was found for generalist species. On acidic soils, the share of forest specialists is generally lower (and thus the share of forest generalists higher) than on base-rich soils, because there is a very limited species pool of forest specialists on acidic soils (Schmidt, Kriebitzsch, & Ewald, 2011).

We have shown over a large geographic gradient that thinning as forest management does not affect forest specialist species richness negatively in ancient forests, while generalists showed a contrasting pattern. Our results underpin how forest management affects edge influences on forest plant biodiversity. We recommend taking this interaction between forest management and edge-to-interior gradients into account in future research as well as in conservation decisions because both modify the microclimate, soil processes and deposition of polluting aerosols. Therefore, this

interaction is key to predicting the effects of global change on forest plants in landscapes characterized by a mosaic of forest patches and agricultural land, which is now typical for many parts of Europe.

ACKNOWLEDGEMENTS

We are grateful to Evy Ampoorter, Shruti Bakshi, Haben Blondeel, Kim Calders, Filip Ceunen, Kris Ceunen, Robbe De Beelde, Emiel De Lombaerde, Lionel Hertzog, Dries Landuyt, Pierre Lhoir, Audrey Peiffer, Sanne Van Den Berge, Lotte Van Nevel and Mia Vedel-Sørensen for their support during the intense fieldwork campaign, to Luc Willems and Greet De Bruyn for the chemical analyses and Abdulwahhab Ghairi for the texture analysis. 'Europe' icon by Denis Sazhin and 'Tree' icon (adapted) by Veremeya, from thenounproject.com (Figure 1).

AUTHORS CONTRIBUTION

PDF, SG, PVG, CM and KV designed the research; all authors collected data; SG performed statistical analyses; SG, with contributions from PDF, PVG and FZ, wrote the paper; all authors discussed the results and commented on the manuscript drafts.

DATA ACCESSIBILITY

Raw data and R code are available at Figshare. <https://doi.org/10.6084/m9.figshare.c.4665125.v1>.

ORCID

Sanne Govaert  <https://orcid.org/0000-0002-8939-1305>
 Camille Meeussen  <https://orcid.org/0000-0002-5869-4936>
 Thomas Vanneste  <https://orcid.org/0000-0001-5296-917X>
 Kurt Bollmann  <https://orcid.org/0000-0002-4690-7121>
 Jörg Brunet  <https://orcid.org/0000-0003-2667-4575>
 Sara A. O. Cousins  <https://orcid.org/0000-0003-2656-2645>
 Martin Diekmann  <https://orcid.org/0000-0001-8482-0679>
 Bente J. Graae  <https://orcid.org/0000-0002-5568-4759>
 Per-Ola Hedwall  <https://orcid.org/0000-0002-0120-7420>
 Thilo Heinken  <https://orcid.org/0000-0002-1681-5971>
 Jonathan Lenoir  <https://orcid.org/0000-0003-0638-9582>
 Michael P. Perring  <https://orcid.org/0000-0001-8553-4893>
 Quentin Ponette  <https://orcid.org/0000-0002-2726-7392>
 Federico Selvi  <https://orcid.org/0000-0002-3820-125X>
 Fabien Spicher  <https://orcid.org/0000-0002-9999-955X>
 Florian Zellweger  <https://orcid.org/0000-0003-1265-9147>
 Kris Verheyen  <https://orcid.org/0000-0002-2067-9108>
 Pieter Vangansbeke  <https://orcid.org/0000-0002-6356-2858>
 Pieter De Frenne  <https://orcid.org/0000-0002-8613-0943>

REFERENCES

- Ash, J., & Barkham, J. (1976). Changes and variability in the field layer of a coppiced woodland in Norfolk, England. *The Journal of Ecology*, 64(2), 697–712. <https://doi.org/10.2307/2258779>
- Aude, E., & Lawesson, J. E. (1998). Vegetation in Danish beech forests: The importance of soil, microclimate and management factors, evaluated by variation partitioning. *Plant Ecology*, 134(1), 53–65. <https://doi.org/10.1023/a:1009720206762>

- Baeten, L., Bauwens, B., De Schrijver, A. N., De Keersmaeker, L., Van Calster, H., Vandekerckhove, K., ... Verheyen, K. (2009). Herb layer changes (1954–2000) related to the conversion of coppice-with-standards forest and soil acidification. *Applied Vegetation Science*, 12(2), 187–197. <https://doi.org/10.1111/j.1654-109X.2009.01013.x>
- Barton, K. (2019). MuMIn: Multi-Model Inference. R package version 1.4 3.6. <https://CRAN.R-project.org/package=MuMIn>
- Bates, D., Machler, M., Bolker, B. M., & Walker, S. C. (2015). Fitting linear mixed-effects models using lme4. *Journal of Statistical Software*, 67(1), 1–48.
- Berges, L., Avon, C., Arnaudet, L., Archaux, F., Chauchard, S., & Dupouey, J. L. (2016). Past landscape explains forest periphery-to-core gradient of understory plant communities in a reforestation context. *Diversity and Distributions*, 22(1), 3–16. <https://doi.org/10.1111/ddi.12384>
- Borchsenius, F., Nielsen, P. K., & Lawesson, J. E. (2004). Vegetation structure and diversity of an ancient temperate deciduous forest in SW Denmark. *Plant Ecology*, 175(1), 121–135. <https://doi.org/10.1023/B:VEGE.0000048095.29961.c5>
- Brunet, J., Falkengren-Grerup, U., & Tyler, G. (1996). Herb layer vegetation of south Swedish beech and oak forests - Effects of management and soil acidity during one decade. *Forest Ecology and Management*, 88(3), 259–272. [https://doi.org/10.1016/s0378-1127\(96\)03845-5](https://doi.org/10.1016/s0378-1127(96)03845-5)
- Brunet, J., Valtinat, K., Mayr, M. L., Felton, A., Lindblad, M., & Bruun, H. H. (2011). Understorey succession in post-agricultural oak forests: Habitat fragmentation affects forest specialists and generalists differently. *Forest Ecology and Management*, 262(9), 1863–1871. <https://doi.org/10.1016/j.foreco.2011.08.007>
- Brus, D. J., Hengeveld, G. M., Walvoort, D. J. J., Goedhart, P. W., Heidema, A. H., Nabuurs, G. J., & Gunia, K. (2012). Statistical mapping of tree species over Europe. *European Journal of Forest Research*, 131(1), 145–157. <https://doi.org/10.1007/s10342-011-0513-5>
- Cadenasso, M. L., & Pickett, S. T. A. (2001). Effect of edge structure on the flux of species into forest interiors. *Conservation Biology*, 15(1), 91–97. <https://doi.org/10.1046/j.1523-1739.2001.99309.x>
- Chen, J. Q., Saunders, S. C., Crow, T. R., Naiman, R. J., Brosfoske, K. D., Mroz, G. D., ... Franklin, J. F. (1999). Microclimate in forest ecosystem and landscape ecology - Variations in local climate can be used to monitor and compare the effects of different management regimes. *BioScience*, 49(4), 288–297. <https://doi.org/10.2307/1313612>
- De Keersmaeker, L., Martens, L., Verheyen, K., Hermy, M., De Schrijver, A., & Lust, N. (2004). Impact of soil fertility and insolation on diversity of herbaceous woodland species colonizing afforestations in Muizen forest (Belgium). *Forest Ecology and Management*, 188(1–3), 291–304. <https://doi.org/10.1016/j.foreco.2003.07.025>
- de Martonne, E. (1926). Une nouvelle fonction climatologique: L'indice d'aridité. *Meteorologie*, 2, 449–459.
- Decocq, G., Aubert, M., Dupont, F., Alard, D., Saguez, R., Watzefranger, A., ... Bardat, J. (2004). Plant diversity in a managed temperate deciduous forest: Understorey response to two silvicultural systems. *Journal of Applied Ecology*, 41(6), 1065–1079. <https://doi.org/10.1111/j.0021-8901.2004.00960.x>
- Devlaeminck, R., Bossuyt, B., & Hermy, M. (2005). Inflow of seeds through the forest edge: Evidence from seed bank and vegetation patterns. *Plant Ecology*, 176(1), 1–17. <https://doi.org/10.1007/s11258-004-0008-2>
- Didham, R. K., & Lawton, J. H. (1999). Edge structure determines the magnitude of changes in microclimate and vegetation structure in tropical forest fragments. *Biotropica*, 31(1), 17–30. <https://doi.org/10.2307/2663956>
- Dodonov, P., Harper, K. A., & Silva-Matos, D. M. (2013). The role of edge contrast and forest structure in edge influence: Vegetation and microclimate at edges in the Brazilian cerrado. *Plant Ecology*, 214(11), 1345–1359. <https://doi.org/10.1007/s11258-013-0256-0>
- Ehrlén, J., & Eriksson, O. (2000). Dispersal limitation and patch occupancy in forest herbs. *Ecology*, 81(6), 1667–1674. [https://doi.org/10.1890/0012-9658\(2000\)081\[1667:Dlapoi\]2.0.Co;2](https://doi.org/10.1890/0012-9658(2000)081[1667:Dlapoi]2.0.Co;2)
- Euro+Med. (2006). Euro+Med PlantBase - the information resource for Euro-Mediterranean plant diversity. Retrieved from <http://ww2.bgbm.org/EuroPlusMed/query.asp>
- Fraver, S. (1994). Vegetation responses along edge-to-interior gradients in the mixed hardwood forests of the Roanoke river basin, North Carolina. *Conservation Biology*, 8(3), 822–832. <https://doi.org/10.1046/j.1523-1739.1994.08030822.x>
- Gehlhausen, S. M., Schwartz, M. W., & Augspurger, C. K. (2000). Vegetation and microclimatic edge effects in two mixed-mesophytic forest fragments. *Plant Ecology*, 147(1), 21–35.
- Gilbert, J., Gowing, D., & Wallace, H. (2009). Available soil phosphorus in semi-natural grasslands: Assessment methods and community tolerances. *Biological Conservation*, 142(5), 1074–1083. <https://doi.org/10.1016/j.biocon.2009.01.018>
- Gilliam, F. S. (2007). The ecological significance of the herbaceous layer in temperate forest ecosystems. *BioScience*, 57(10), 845–858. <https://doi.org/10.1641/B571007>
- Godefroid, S., & Koedam, N. (2003). Distribution pattern of the flora in a peri-urban forest: An effect of the city-forest ecotone. *Landscape and Urban Planning*, 65(4), 169–185. [https://doi.org/10.1016/s0169-2046\(03\)00013-6](https://doi.org/10.1016/s0169-2046(03)00013-6)
- Grayson, S. F., Buckley, D. S., Henning, J. G., Schweitzer, C. J., Gottschalk, K. W., & Loftis, D. L. (2012). Understorey light regimes following silvicultural treatments in central hardwood forests in Kentucky, USA. *Forest Ecology and Management*, 279, 66–76. <https://doi.org/10.1016/j.foreco.2012.05.017>
- Guirado, M., Pino, J., & Rodà, F. (2006). Understorey plant species richness and composition in metropolitan forest archipelagos: Effects of forest size, adjacent land use and distance to the edge. *Global Ecology and Biogeography*, 15(1), 50–62. <https://doi.org/10.1111/j.1466-822X.2006.00197.x>
- Haddad, N. M., Brudvig, L. A., Clobert, J., Davies, K. F., Gonzalez, A., Holt, R. D., ... Townshend, J. R. (2015). Habitat fragmentation and its lasting impact on Earth's ecosystems. *Science Advances*, 1(2), e1500052. <https://doi.org/10.1126/sciadv.1500052>
- Hansen, M. C., Potapov, P. V., Moore, R., Hancher, M., Turubanova, S. A., Tyukavina, A., ... Townshend, J. R. G. (2013). High-resolution global maps of 21st-century forest cover change. *Science*, 342(6160), 850–853. <https://doi.org/10.1126/science.1244693>
- Harper, K. A., & Macdonald, S. E. (2011). Quantifying distance of edge influence: A comparison of methods and a new randomization method. *Ecosphere*, 2(8), 17. <https://doi.org/10.1890/es11-00146.1>
- Harper, K. A., Macdonald, S. E., Burton, P. J., Chen, J., Brosfoske, K. D., Saunders, S. C., ... Esseen, P.-A. (2005). Edge influence on forest structure and composition in fragmented landscapes. *Conservation Biology*, 19(3), 768–782. <https://doi.org/10.1111/j.1523-1739.2005.00045.x>
- Heinken, T., Diekmann, M., Liira, J., Orczewska, A., Brunet, J., Chytrý, M., ... Wulf, M. (2019). European forest plant species list. *Figshare*. <https://doi.org/10.6084/m9.figshare.8095217>
- Hermy, M. (2015). Evolution and changes in the understorey of deciduous forests: Lagging behind drivers of change. In K. Kirby, & C. Watkins (Eds.), *Europe's changing woods forests: From wildwood to managed landscapes* (pp. 174–192). Wallingford, UK: CAB International.
- Hijmans, R. J. (2019). raster: Geographic Data Analysis and Modeling. R package version 2.8-19. Retrieved from <https://CRAN.R-project.org/package=raster>
- Honnay, O., Verheyen, K., & Hermy, M. (2002). Permeability of ancient forest edges for weedy plant species invasion. *Forest Ecology and Management*, 161(1–3), 109–122. [https://doi.org/10.1016/S0378-1127\(01\)00490-X](https://doi.org/10.1016/S0378-1127(01)00490-X)

- ISO 11263 (1994). Soil quality – Determination of phosphorus – Spectrometric determination of phosphorus soluble in sodium hydrogen carbonate solution.
- ISO 11277 (2009). Soil quality – Determination of particle size distribution in mineral soil material – Method by sieving and sedimentation ISO, Geneva.
- Jamoneau, A., Sonnier, G., Chabrierie, O., Closset-Kopp, D., Saguez, R., Gallet-Moron, E., & Decocq, G. (2011). Drivers of plant species assemblages in forest patches among contrasted dynamic agricultural landscapes. *Journal of Ecology*, 99(5), 1152–1161. <https://doi.org/10.1111/j.1365-2745.2011.01840.x>
- Karger, D. N., Conrad, O., Böhrer, J., Kawohl, T., Kreft, H., Soria-Auza, R. W., ... Kessler, M. (2017). Climatologies at high resolution for the earth's land surface areas. *Scientific Data*, 4(1), 170122. <https://doi.org/10.1038/sdata.2017.122>
- Lajtha, K., Driscoll, C., Jarrell, W., & Elliott, E. (1999). Soil phosphorus: Characterization and total element analysis. In G. P. Robertson, D. C. Coleman, C. S. Bledsoe, & P. Sollins (Eds.), *Standard soil methods for long-term ecological research* (pp. 115–142). New York, NY: Oxford University Press.
- Landuyt, D., De Lombaerde, E., Perring, M. P., Hertzog, L. R., Ampoorter, E., Maes, S. L., ... Verheyen, K. (2019). The functional role of temperate forest understorey vegetation in a changing world. *Global Change Biology*, 25(11), 3625–3641. <https://doi.org/10.1111/gcb.14756>
- Matlack, G. R. (1993). Microenvironment variation within and among forest edges in the eastern United States. *Biological Conservation*, 66(3), 185–194. [https://doi.org/10.1016/0006-3207\(93\)90004-k](https://doi.org/10.1016/0006-3207(93)90004-k)
- Millennium Ecosystem Assessment. (2005). *Ecosystems and human well-being: Biodiversity synthesis*. Washington, DC: Millennium Ecosystem Assessment.
- Murcia, C. (1995). Edge effects in fragmented forests: Implications for conservation. *Trends in Ecology & Evolution*, 10(2), 58–62. [https://doi.org/10.1016/S0169-5347\(00\)88977-6](https://doi.org/10.1016/S0169-5347(00)88977-6)
- Orczewska, A., & Glista, A. (2005). Floristic analysis of the two woodland-meadow ecotones differing in orientation of the forest edge. *Polish Journal of Ecology*, 53(3), 365–382.
- Paal, T., Kuett, L., Lohmus, K., & Liira, J. (2017). Both spatiotemporal connectivity and habitat quality limit the immigration of forest plants into wooded corridors. *Plant Ecology*, 218(4), 417–431. <https://doi.org/10.1007/s11258-017-0700-7>
- Pellissier, V., Bergès, L., Nedeltcheva, T., Schmitt, M. C., Avon, C., Cluzeau, C., & Dupouey, J. L. (2013). Understorey plant species show long-range spatial patterns in forest patches according to distance-to-edge. *Journal of Vegetation Science*, 24(1), 9–24. <https://doi.org/10.1111/j.1654-1103.2012.01435.x>
- Perring, M. P., Bernhardt-Römermann, M., Baeten, L., Midolo, G., Blondeel, H., Depauw, L., ... Verheyen, K. (2018). Global environmental change effects on plant community composition trajectories depend upon management legacies. *Global Change Biology*, 24(4), 1722–1740. <https://doi.org/10.1111/gcb.14030>
- Pielou, E. C. (1966). The measurement of diversity in different types of biological collections. *Journal of Theoretical Biology*, 13, 131–144. [https://doi.org/10.1016/0022-5193\(66\)90013-0](https://doi.org/10.1016/0022-5193(66)90013-0)
- R Core Team. (2018). *R: A language and environment for statistical computing*. Vienna, Austria: R Foundation for Statistical Computing. Retrieved from <https://www.R-project.org/>
- Remy, E., Wuyts, K., Boeckx, P., Ginzburg, S., Gundersen, P., Demey, A., ... Verheyen, K. (2016). Strong gradients in nitrogen and carbon stocks at temperate forest edges. *Forest Ecology and Management*, 376, 45–58. <https://doi.org/10.1016/j.foreco.2016.05.040>
- Ries, L., Fletcher, R. J. Jr, Battin, J., & Sisk, T. D. (2004). Ecological responses to habitat edges: Mechanisms, models, and variability explained. *Annual Review of Ecology, Evolution, and Systematics*, 35, 491–522. <https://doi.org/10.1146/annurev.ecolsys.35.112202.130148>
- Saunders, D. A., Hobbs, R. J., & Margules, C. R. (1991). Biological consequences of ecosystem fragmentation - a review. *Conservation Biology*, 5(1), 18–32. <https://doi.org/10.1111/j.1523-1739.1991.tb00384.x>
- Schmidt, M., Kriebitzsch, W.-U., & Ewald, J. (2011). *Waldartenlisten der Farn- und Blütenpflanzen, Moose und Flechten Deutschlands*. Bonn, Germany: BfN.
- Schmidt, M., Lischeid, G., & Nendel, C. (2019). Microclimate and matter dynamics in transition zones of forest to arable land. *Agricultural Forest Meteorology*, 268, 1–10. <https://doi.org/10.1016/j.agrfor.2019.01.001>
- Schuster, B., & Diekmann, M. (2003). Changes in species density along the soil pH gradient - Evidence from German plant communities. *Folia Geobotanica*, 38(4), 367–379. <https://doi.org/10.1007/bf02803245>
- Scolastri, A., Cancellieri, L., Iocchi, M., & Cutini, M. (2017). Old coppice versus high forest: The impact of beech forest management on plant species diversity in central Apennines (Italy). *Journal of Plant Ecology*, 10(2), 271–280. <https://doi.org/10.1093/jpe/rtw034>
- Secretariat of the Convention on Biological Diversity (CBD). (2010). *Global Biodiversity Outlook 3*. Montréal, QC: Secretariat of the Convention on Biological Diversity.
- Strubelt, I., Diekmann, M., Griese, D., & Zacharias, D. (2019). Inter-annual variation in species composition and richness after coppicing in a restored coppice-with-standards forest. *Forest Ecology and Management*, 432, 132–139. <https://doi.org/10.1016/j.foreco.2018.09.014>
- Takkis, K., Kull, T., Hallikma, T., Jaksi, P., Kaljund, K., Kauer, K., ... Laanisto, L. (2018). Drivers of species richness and community integrity of small forest patches in an agricultural landscape. *Journal of Vegetation Science*, 29(6), 978–988. <https://doi.org/10.1111/jvs.12689>
- Thimonier, A., Dupouey, J. L., & Timbal, J. (1992). Floristic changes in the herb-layer vegetation of a deciduous forest in the Lorraine plain under the influence of atmospheric deposition. *Forest Ecology and Management*, 55(1–4), 149–167. [https://doi.org/10.1016/0378-1127\(92\)90098-t](https://doi.org/10.1016/0378-1127(92)90098-t)
- Tuff, K., Tuff, T., & Davies, K. J. E. I. (2016). A framework for integrating thermal biology into fragmentation research. *Ecology Letters*, 19(4), 361–374. <https://doi.org/10.1111/ele.12579>
- Vallet, J., Beaujouan, V., Pithon, J., Roze, F., & Daniel, H. (2010). The effects of urban or rural landscape context and distance from the edge on native woodland plant communities. *Biodiversity and Conservation*, 19(12), 3375–3392. <https://doi.org/10.1007/s10531-010-9901-2>
- Vellend, M., Verheyen, K., Jacquemyn, H., Kolb, A., Van Calster, H., Peterken, G., & Hermy, M. (2006). Extinction debt of forest plants persists for more than a century following habitat fragmentation. *Ecology*, 87(3), 542–548. <https://doi.org/10.1890/05-1182>
- Verheyen, K., Baeten, L., De Frenne, P., Bernhardt-Römermann, M., Brunet, J., Cornelis, J., ... Verstraeten, G. (2012). Driving factors behind the eutrophication signal in understorey plant communities of deciduous temperate forests. *Journal of Ecology*, 100(2), 352–365. <https://doi.org/10.1111/j.1365-2745.2011.01928.x>
- Whigham, D. E. (2004). Ecology of woodland herbs in temperate deciduous forests. *Annual Review of Ecology Evolution and Systematics*, 35, 583–621. <https://doi.org/10.1146/annurev.ecolsys.35.021103.105708>
- Widenfalk, O., & Weslien, J. (2009). Plant species richness in managed boreal forests—Effects of stand succession and thinning. *Forest Ecology and Management*, 257(5), 1386–1394. <https://doi.org/10.1016/j.foreco.2008.12.010>
- Willi, J. C., Mountford, J. O., & Sparks, T. H. (2005). The modification of ancient woodland ground flora at arable edges. *Biodiversity*

and *Conservation*, 14(13), 3215–3233. <https://doi.org/10.1007/s10531-004-0443-3>

Wright, T. E., Kasel, S., Tausz, M., & Bennett, L. T. (2010). Edge microclimate of temperate woodlands as affected by adjoining land use. *Agricultural and Forest Meteorology*, 150(7–8), 1138–1146. <https://doi.org/10.1016/j.agrformet.2010.04.016>

Zuur, A. F., Ieno, E. N., & Elphick, C. S. (2010). A protocol for data exploration to avoid common statistical problems. *Methods in Ecology & Evolution*, 1(1), 3–14. <https://doi.org/10.1111/j.2041-210X.2009.00001.x>

SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

Appendix S1. Study site description per transect

Appendix S2. Protocol for site selection

Appendix S3. Quantification of the forest management types

Appendix S4. List of species observed per region with forest guild association

Appendix S5. Shade casting ability (SCA) index scores per species

Appendix S6. Correlation between variables

Appendix S7. Closed forest species richness results

Appendix S8. Parameter estimates

How to cite this article: Govaert S, Meeussen C, Vanneste T, et al. Edge influence on understorey plant communities depends on forest management. *J Veg Sci.* 2020;31:281–292. <https://doi.org/10.1111/jvs.12844>