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Article

Shaping the Ecotone Zone in Forest Communities That Are Adjacent to Expressway Roads

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Abstract: As a result of forest fragmentation, ecotones have become an important contribution to the landscape. The areas that include ecotones are constantly growing, thus creating new habitats for plants and animals. The factor that has the greatest impact on the configuration and extent of an ecotone is called the "edge effect". The aim of this study was to determine the width of the ecotones in forests that are adjacent to an expressway and to characterize the edge effect they produced. The research was performed along ten transects situated at the edge of a forest and in the interior part of a forest (plots from 0 to 200 m). The structures of the forest stand, trees, shrubs, dwarf shrubs and herbs were determined and data on the species composition and species cover were also collected. Results of the statistical analyses (linear mixed models as well as detrended and canonical correspondence analyses) indicated significant changes in the structure, species composition, and species turnover that were dependent on the distance from the edge of the forest. It was shown that shrubs (cover, density, species richness) were the most affected while vascular plants were the least affected. However, the changes were ambiguous. There was either an increase or decrease in the individual parameters of the forest structure and the coverage of forest species. The extent of the forest edge began at a minimum distance of 0–20 m.

Keywords: edge effect; forest ecotone; expressways; fragmentation; forest margin

1. Introduction

Forest fragmentation, which is an ongoing process, leads to the creation of numerous forest edges. These types of ecotones become significant elements of heterogeneous landscapes. Natural ecotones are valuable habitats for biodiversity, and protect the interior of forests. Both natural and human well-developed ecotones are often local hotspots, refugia, and migration pathways for plants and animals, thus enabling inter-population contacts. Ecotones are a place where they feed, breed, and winter [1–3]. The vegetation of an ecotone zone is unique, and therefore the presence of both forest and non-forest species as well as the presence of species that are specific for this type of habitat are necessary. Changes in the abiotic and biotic conditions in the edges compared to the interior habitat constitute the edge effect. An indication of the emergence of an edge effect in some ecotone zones is an increase in biodiversity both in terms of the number of species and the life forms of the species that are represented [1–3].

Research has shown a relationship between the state of the vegetation in the ecotone zone and biotic resistance in the deeper areas of a forest. Stable and naturally developed vegetation of the forest edge constitutes a specific buffer for the spread of non-forest species deep into forests, including alien and invasive species as well as "pests" of timber plantations [4]. Furthermore, it also affects the behavior of environmental conditions including temperature and reduces the spread of dust and harmful gases from the ambient

environment into the forest, thereby protecting sensitive species and allowing optimal growth for a forest stand [5].

Ecotones are still zones that are insufficiently understood in ecological science, which is due to this high variability that depends on, e.g., the history, orientation, climate, management and humidity of the edge [6,7]. The nature of the ecotone and its resulting edge effect are influenced by the exposure of the forest edge (margin), the quality and type of soils on which they occur, and the diversity of the forests, either natural, or resulting from management [8]. The genesis of the edge of a forest also plays a key role in shaping it. There are both natural and anthropogenic ecotones. In order to maintain the edge of natural forests, some human-made disturbance is allowed; however, the intensity of these activities is limited to those that will not cause excessive interference with the forest environment. Submitting the edge of a forest to continuous anthropogenic disturbances has a destructive effect on the condition and durability of the ecotone, which results in loss of functionality and structure. Negative impacts on forest edges can happen from the surroundings or from inadequately performed forest management in the ecotone zone itself [4,9].

The need for protecting and monitoring ecotone zones has been stressed because they are considered to be indicators of any changes in the environment. In these zones, changes such as the disappearance of sensitive species and the influx of species with different habitat requirements are the fastest. This is caused by the high susceptibility of an ecotone zone to climate changes and the influence of the surrounding environment [7]. Still, research conducted in ecotone zones to date has not used a uniform methodology [10]. Additionally, forest edges are spatially and temporally diversified [11]. There is a lack of extensive research that analyzes the diversity of the structure and composition of a forest edge stand [7]. Both forest management and the microclimate vary by region and shape the edge structure on a local scale. The high degree of variability in the edge influences indicates the subject matter for detailed research for a specific location. Detailed knowledge about the edge effect enables management guidelines to be prepared that are relative to the specificity and context of a region [6,7].

Furthermore, the characteristics, conditions, and extent of ecotonic zones in some countries may have changed recently as a result of increased urbanization of the environments surrounding forest communities, the intensification of forest management in these communities, and climate change. It is important to actually determine the width of the ecotone in forests that are adjacent to expressways, where the limitation or complete abandonment of forest management might prevent the spread of environmental pollutants that are emitted in areas adjacent to the forests.

In particular, we wanted to examine to what extent the effect of a road influences the structure of a tree stand and species composition in a forest ecotone. The magnitude of the effect of a road will be variable and will have a greater impact on the qualitative parameters (species composition) than on the quantitative parameters (tree stand and understory structure). We hypothesized that forests that are situated closer to a road would be less diverse in terms of species composition and characterized by a greater abundance of invasive alien and expansive native species. In addition, we expected that more light-demanding species would prefer forest edge sites.

2. Materials and Methods

2.1. Study Area

The study was conducted in the Rybnik Plateau, the Pszczyna Lowland, and the Silesian Foothills in southern Poland (Figure 1). Data were collected in a mixed coniferous forest and a mixed deciduous forest. This region has a moderate climate (mean annual temperature: 7 °C, annual precipitation: 700–800 mm). Podzolic and brown soils predominate, with some fen soils in the river valley.
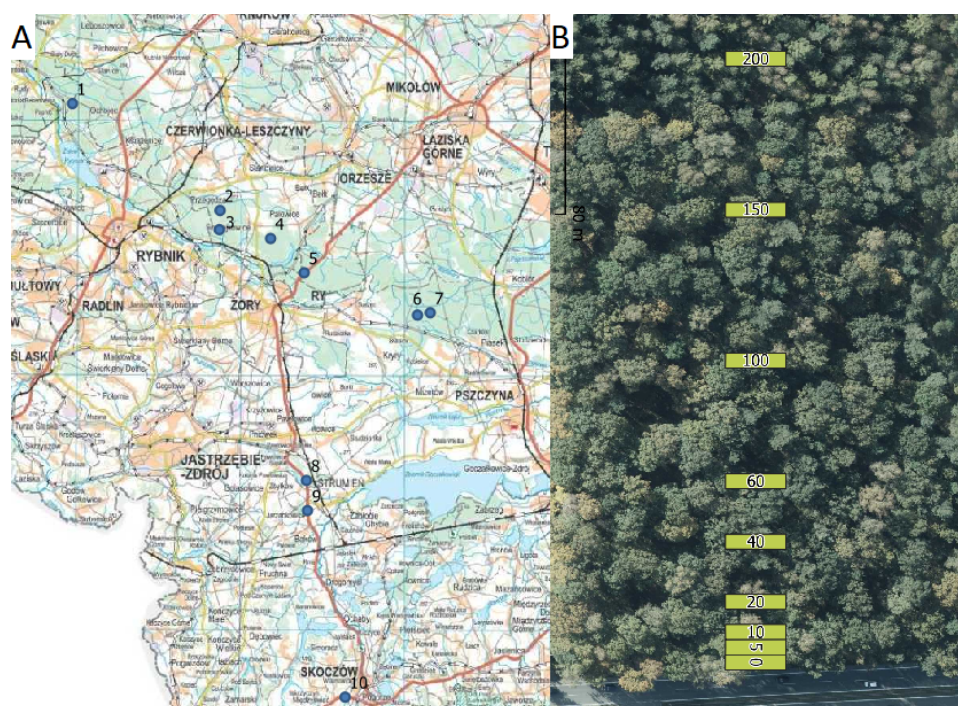
Figure 1. The location of ten transects in the study area in southern Poland (**A**) and the location of nine plots within a transect (**B**).

The research was conducted in forest communities that are adjacent to a trunk road (DK 81) and a regional road (number S1, E75/E462) with average daily traffic of between 16,488 and 22,317 motor vehicles. The forest stands ranged in age from 39 to 108 years and included communities such as: coniferous forests *Calamagrostio vilosae-Pinetum, Molinio caeruleae-Pinetum*, an ash-alder riparian forest *Fraxino-Alnetum*, a beech forest *Luzulo pilosae-Fagetum*, mixed coniferous forests *Pinus sylvestris-Carex brizoides, Querco roboris-Pinetum*, and an oak-hornbeam forest *Tilio-Carpinetum*.

2.2. Data Collection

The data were collected following two types of transects: in the interior part of a forest (interior) and at the edge of a forest (margin) at a minimum distance of 0 m to 200 m from the roads. The transects in the interior part of the forest were established in the depths of large forest complexes at a minimum distance of 400 m to 1820 m from any buildings or roads. The transects in the ecotone zone were situated perpendicular to the edge of the forest and began at its border. Six transects were identified in the interior part of a forest and four transects in the ecotone zone. Each of the transects was 205 m long and consisted of nine study plots. The study plots were 20 m × 5 m in size and were arranged within 0, 5, 10, 20, 40, 60, 100, 150, and 200 m from the edge of each transect. The longer side of each study plot was parallel to the forest border. Sixteen response variables were considered. For trees >5 cm diameter at breast height and >50 cm tall, data were collected on the 20 m × 5 m plots. Species identity, diameter at breast height (DBH), and height were recorded. For the shrub layer, the percent cover of all of the shrub and sapling species was estimated in two 1 m × 1 m subplots within the plots. Additionally, the number and heights of saplings and shrubs as well as dwarf woody species were also counted. In the herb layer, the cover was estimated by determining the amount of soil cover in percentage by the vertical projection of the above-ground parts of herbs in the area of three test plots with dimensions of 0.5 m × 0.5 m within a test field with dimensions of 5 × 20 m [12,13], and the species were identified [14,15]. Based on the species cover, the Shannon-Wiener index and species richness were calculated for all of these groups. The response variables are listed in Table 1.

Table 1. The list of studied parameters—response variables of the influence of the edge.

Code	Name of Variable	Type
TrDHa	Tree density per hectare	Numerical
ShD	Shrub density	Numerical
DsD	Dwarf shrub density	Numerical
ShC	Shrub cover	Percent cover
DsC	Dwarf shrubs cover	Percent cover
VpC	Herb vascular plant cover	Percent cover
TrH	Trees Shannon-Wiener index	Numerical
ShH	Shrubs Shannon-Wiener index	Numerical
DsH	Dwarf shrubs Shannon-Wiener index	Numerical
VpH	Vascular plants Shannon-Wiener index	Numerical
TrG	Mean tree girth	Numerical
TrHeight	Mean tree height	Numerical
ShSr	Shrub species richness	Integer
DsSr	Dwarf shrub species richness	Integer
VpSr	Vascular plant species richness	Integer
TrSr	Tree species richness	Integer

In order to assess the habitat conditions, the Ellenberg indicator values (EIV) for light (L), temperature (T), moisture (F), continentality (K), soil reaction (R), and nitrogen (N) were calculated. The weighted-cover values of EIV were also calculated except for the species that were assigned as x in Ellenberg and Leuchsner [16]. The slope and aspect of the plots were also determined using clinometer and compass. For the statistical analyses, the degrees of the aspect were rescaled from 0–360° to 0–180° so that $n = 0°$ and $S = 180°$. This procedure took into account the fact that the S-facing slopes receive more light and therefore have the highest temperature [17,18]. The number of species (S), Shannon-Wiener diversity index (H), and Pielou's evenness index (E) were calculated for each study plot and separately for the trees, shrubs, and herbs.

2.3. Data Analysis

All of the statistical analyses were performed using the R language and environment [19]. To assess the species turnover between and within the forest interior and forest margin, the Whittaker [20] formula for measuring beta diversity was used, following:

$$\beta w = (a + b + c)/(2a + b + c)/2, \tag{1}$$

where a = number of species that are common to both sites, b = number of species that occur on site 1 but not on site 2, and c = number of species that occur on site 2 but not on site 1.

To analyze the indicator species for forest edge, more confined to this habitat type, "edge-positive", and interior forest "edge-negative", we used the indicator species analysis (ISA) of the "indicspecies" package and the *multipatt()* function. The function follows the IndVal method [21] as modified by De Cáceres et al. [22]. The affinity of a species to a specific habitat was measured using IndVal (indicator value), which ranges from 0 to 1. The statistical significance of this relationship was determined using a permutation test (999 iterations). Only those indicator species for the groups of sites that had a statistically significant IndVal are presented.

In order to examine any differences in species composition along the distance from the edge and under the impact of other environmental factors, a canonical correspondence analysis (CCA) was performed using the "vegan" package and *cca()* function. Only three environmental factors were used: distance, slope, and aspect. A permutation test with 999 iterations was conducted to assess the significance of the impact of the variables. Variance partitioning among the distance, aspect, and slope was calculated and is shown on Venn diagrams. A detrended correspondence analysis (DCA) was performed using the *vegan*::*decorana()* function. To determine how the groups of species and species associations

with the habitats were correlated with the gradients that were obtained, the *vegan::envfit()* function [23] for the passive projection of the environmental factors, EIVs, and cover of understory species (shrubs, dwarfs, and herbs) was run.

In order to assess the significance of the influence of an edge on the structure of a tree stand of forest vegetation, 16 response variables mentioned earlier were taken into account (Table 1). The edge effect was considered to be a fixed variable (Dist) with two levels (margin, interior), and the distance of each study plot from the forest edge was treated as a continuous variable (in meters). The linear mixed model (LMM) tests with a Gaussian distribution for the continuous variable or the Poisson distribution for the number of species (integer character) were performed using the "lme4" package and *lmer()* function. In all of the tests, the transect was considered to be a random effect. The significance of the final model, with a presentation of the Wald chi-square statistics and the *p*-values of each of the covariates, was determined using the "car" package and the *Anova()* function. When the Dist was significant, the marginal means were calculated (package emmeans) in order to exclude any fraction under the impact of the transect.

3. Results

A total of 65 vascular plant species from 260 subplots in 10 transects were recorded. There was a higher within-habitat species turnover in the forest edge plots (0.74) when compared to forest interior. The highest among-habitat species turnover was between the forest interior and the forest edge zone and amounted to 0.44 (Table 2), which proves the migration of flora species between these two habitats. It was higher than that between specific groups and total flora.

Table 2. Species richness within and among the types of transects according to Whittaker's species turnover.

	Forest Interior (*n* = 161)	Forest Edge (*n* = 108)	Total (*n* = 269)
Number of species	36	54	65
Species turnover:			
Forest edge	0.444	-	-
Total	0.093	0.287	-
Mean (min, max)	0.71 (0; 10)	0.74 (0; 1)	0.80 (0; 1)

The "edge-positive" and "edge-negative" were distinguished using the IndVal method. Eight species were significantly associated with the forest interiors and 13 with the forest margin (edge), including the invasive alien *Impatiens parviflora* and the expansive native *Carex brizoides* (Table 3).

Table 3. Lists of species relative to their preferences of occurrence found during the research. Explanations: * *p* < 0.05, ** *p* < 0.01, *** *p* < 0.001.

Forest Interior		Forest Margin	
	IndVal		IndVal
Pteridium aquilinum	0.700 ***	*Carex brizoides*	0.610 ***
Trientalis europaea	0.650 ***	*Frangula alnus*	0.506 ***
Quercus petraea	0.488 ***	*Impatiens parviflora*	0.419 ***
Calamagrostis villosa	0.476 ***	*Rubus* sp.	0.419 ***
Fagus sylvatica	0.423 ***	*Populus tremula*	0.386 ***
Pinus sylvestris	0.305 **	*Sambucus nigra*	0.385 ***
Vaccinium vitis-idaea	0.284 **	*Padus avium*	0.373 ***
Maianthemum bifolium	0.209 *	*Corylus avellana*	0.347 ***
-		*Acer platanoides*	0.289 ***
-		*Athyrium filix-femina*	0.272 **
-		*Acer pseudoplatanus*	0.272 ***

Table 3. *Cont.*

Forest Interior	Forest Margin	
-	*Ulmus glabra*	0.272 **
-	*Quercus robur*	0.262 *
-	*Galeobdolon luteum*	0.236 **
-	*Viola reichenbachiana*	0.236 **
-	*Stellaria media*	0.215 *
-	*Dryopteris filix-mas*	0.213 *
-	*Lysimachia vulgaris*	0.192 *

The CCA analysis demonstrated that all of the environmental factors that were used had an impact on the species composition (Table 4), while distance explained the highest fraction of variance (Figure 2). The distance correlated with the second axis of the CCA, whereas aspect and slope correlated with the first axis of the CCA (Figure 2).

Table 4. The CCA decomposition and parameters of the explanatory variables fitted to the results of the DCA analysis.

|	CCA1	CCA2	Pseudo-F	Pr (>F)
eigenvalues	0.4942	0.2901	-	-
distance	0.6034	0.79555	8.5903	0.001
slope	−0.9250	0.37538	9.8854	0.001
aspect	−0.3526	−0.06156	2.6460	0.001
	DCA1	**DCA2**	**r²**	**Pr (>r)**
eigenvalues	0.6314	0.5178	-	-
herbs	0.03278	−0.99946	0.0668	0.001
shrubs	0.94226	0.33488	0.1509	0.001
dwarfs	−0.72471	0.68906	0.4917	0.001
L	−0.99501	0.09976	0.0546	0.001
T	−0.30663	0.95183	0.0301	0.028
K	−0.62909	−0.77733	0.0106	NS
F	0.74783	−0.66389	0.0990	0.001
R	0.99998	−0.00672	0.6353	0.001
N	0.92743	0.37400	0.5578	0.001
S	−0.19523	0.98076	0.2270	0.001
H	−0.24658	0.96912	0.2486	0.001
E	−0.26915	0.96310	0.0739	0.001
Community	-	-	0.5403	0.001
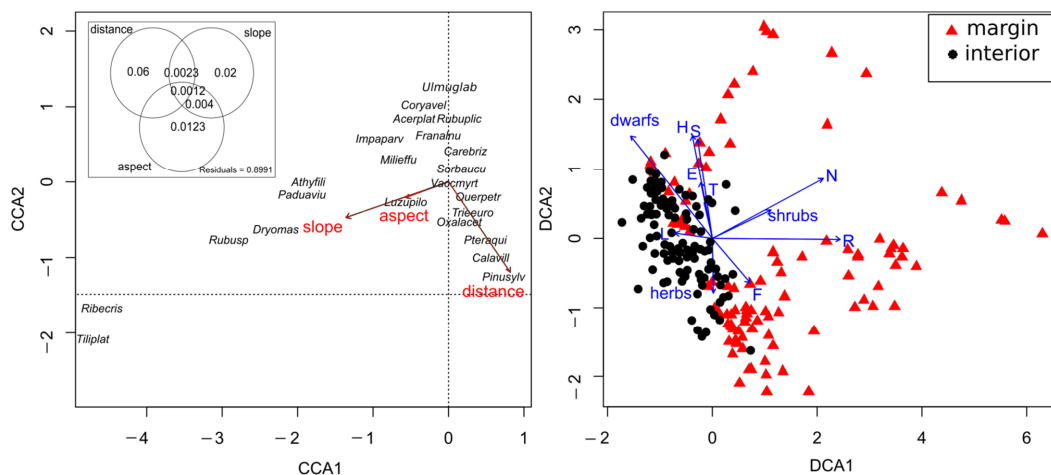
Figure 2. The biplot of the CCA ordination of the plots with statistically significant environmental variables (**left**), and the biplot of the DCA with the statistically significant (*p* < 0.05) passively projected variables (**right**).

The DCA analysis and the fit of explanatory variables showed that the species composition significantly differed between the forest margin and forest interior (Figure 2, Table 4). Dwarfs and herbs as well as all of the biodiversity indices were more associated with the forest interior, while the EIV for nitrogen and soil reaction were more confined to the forest margin (Figure 2).

Among the 16 response variables, only eight were found to be significant in the LMM model with a continuous distance and three variables in the LMM model with distance as a factor (forest interior vs. forest margin) (Figure 3, Table 5).
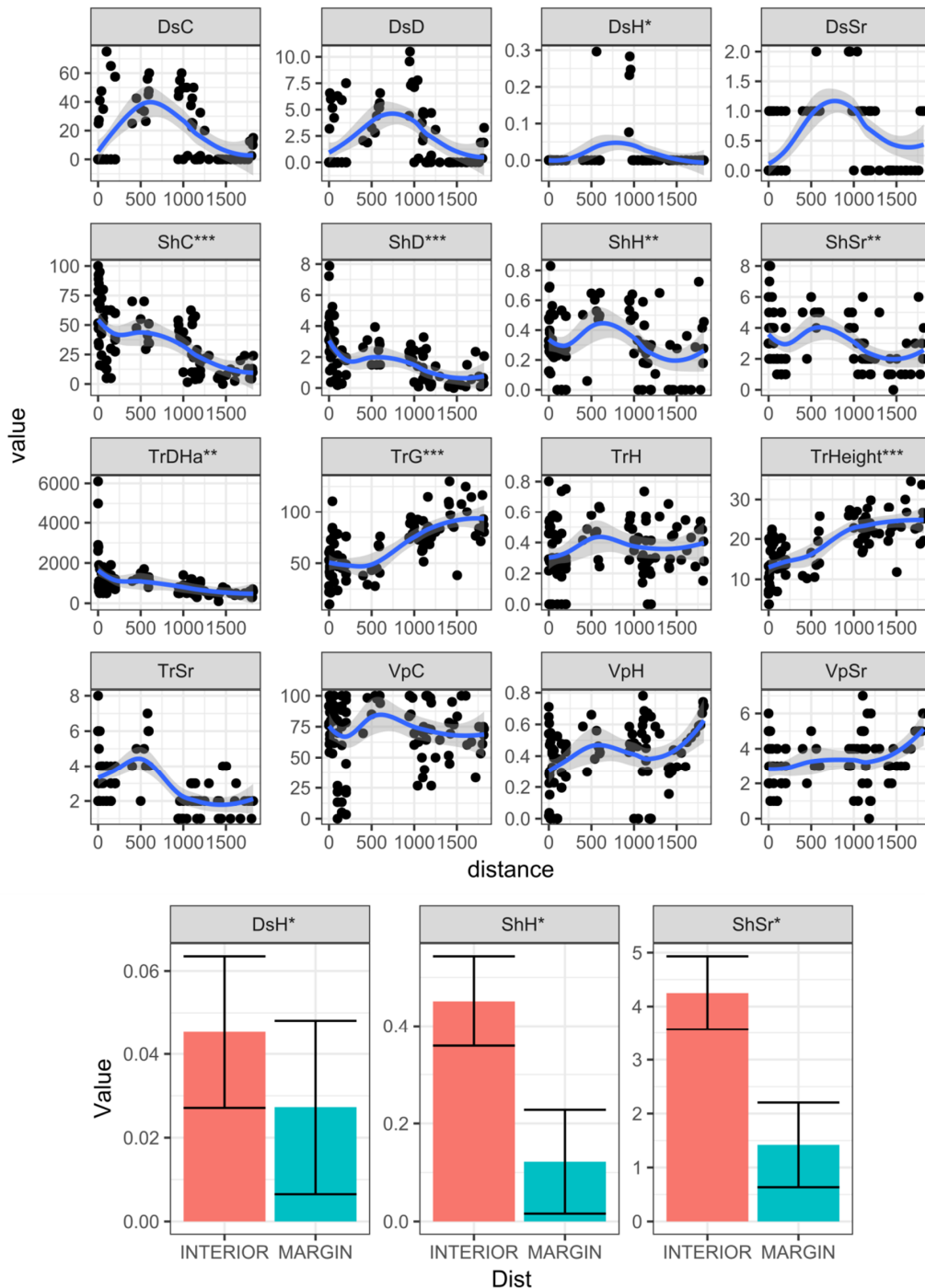

Figure 3. The relationships between the selected variables and distance were examined using LMM. The marginal means ± SE of response variables relative to the interior and margin. Explanations: * *p* < 0.05, ** *p* < 0.01, *** *p* < 0.001. The codes of the variables are listed in Table 1.

Table 5. Results of the LMM tests: coefficients and Wald test statistics. Codes of the variables (Table 1).

Variable		Coefficients of Model					Wald Test Statistics		
		Estimate	SE	df	t	*p*-Value	Chisq	Df	*p*-Value
TrDHa	(Intercept)	1592.88	317.54	102.00	5.02	0.00			
	distance	−0.73	0.26	102.00	−2.85	0.01	8.1002	1	0.004426
	Dist = MARGIN	−177.97	315.09	102.00	−0.57	NS	0.319	1	NS
ShD	(Intercept)	4.04	0.80	11.30	5.02	0.000			
	distance	0.00	0.00	11.68	−3.68	0.003	13.549	1	0.000233
	Dist = MARGIN	−1.54	0.81	10.45	−1.90	NS	3.6049	1	NS
DsD	(Intercept)	3.78	2.06	27.44	1.83	NS			
	distance	0.00	0.00	38.09	−0.71	NS	0.5081	1	NS
	Dist = MARGIN	−2.34	2.22	19.39	−1.05	NS	1.1079	1	NS
ShC	(Intercept)	77.44	14.34	14.96	5.40	0.00			
	Distance	−0.04	0.01	15.90	−3.86	0.0014	14.908	1	0.000113
	Dist = MARGIN	−26.73	14.63	13.52	−1.83	NS	3.3373	1	NS
DsC	(Intercept)	25.14	16.93	23.56	1.48	NS			
	distance	−0.01	0.01	32.32	−0.44	NS	0.1926	1	NS
	Dist = MARGIN	−12.75	18.13	16.81	−0.70	NS	0.4944	1	NS
VpC	(Intercept)	65.12	20.49	34.02	3.18	0.00			
	distance	0.01	0.02	56.76	0.33	NS	0.1091	1	NS
	Dist = MARGIN	6.85	22.73	21.17	0.30	NS	0.0908	1	NS
TrH	(Intercept)	0.49	0.11	11.21	4.35	0.00111			
	distance	0.00	0.00	11.72	−1.85	NS	3.4099	1	NS
	Dist = MARGIN	−0.06	0.11	10.28	−0.52	NS	0.2688	1	NS
ShH	(Intercept)	0.65	0.15	15.80	4.50	0.000			
	distance	0.00	0.00	16.86	−2.63	0.018	6.8907	1	0.008665
	Dist = MARGIN	−0.33	0.15	14.23	−2.22	0.043	4.912	1	0.026671
DsH	(Intercept)	0.08	0.03	12.41	2.66	0.020			
	distance	0.00	0.00	12.76	−2.05	NS	4.1856	1	0.04077
	Dist = MARGIN	−0.07	0.03	11.51	−2.51	0.0284	6.2761	1	0.01224
VpH	(Intercept)	0.34	0.15	17.60	2.20	0.0411			
	distance	0.00	0.00	19.35	0.69	NS	0.48	1	NS
	Dist = MARGIN	−0.02	0.16	15.37	−0.13	NS	0.0156	1	NS
TrG	(Intercept)	36.02	8.14	102.00	4.43	0.00			
	distance	0.04	0.01	102.00	5.57	0.00	30.98	1	0.00
	Dist = MARGIN	11.04	8.08	102.00	1.37	NS	1.8677	1	NS
TrHeight	(Intercept)	14.15	2.20	11.22	6.44	0.00			
	distance	0.01	0.00	11.39	3.96	0.00	15.708	1	0.0001
	Dist = MARGIN	−0.90	2.19	10.31	−0.41	NS	0.1675	1	NS
DsD	(Intercept)	3.78	2.06	27.44	1.83	NS			
	distance	0.00	0.00	38.09	−0.71	NS	0.5081	1	NS
	Dist = MARGIN	−2.34	2.22	19.39	−1.05	NS	1.1079	1	NS
ShSr	(Intercept)	6.14	1.06	13.35	5.77	0.00			
	distance	0.00	0.00	13.99	−3.34	0.00	11.14	1	0.00
	Dist = MARGIN	−2.83	1.08	12.22	−2.62	0.02	6.88	1	0.01

A humped-back relationship was revealed for the dwarf shrubs (cover, species density, species richness), which was only significant for the Shannon-Wiener index, while for the shrubs, a nonlinear relationship with a decrease and an increase was generally observed, which was significant for all of the variables. For the tree species and vascular plants, there was an increase in the parameters, but in the latter, it was a non-significant relationship (Figure 3).

4. Discussion

Our results showed that the edge effect is mostly manifested in a greater structural diversity, especially in shrubs, saplings, and a greater number of shorter trees. In general, woody plants and herbs close to roads had lower heights but maximum values were obtained between 500 m to 1500 m, depending on the type of plant. Trees had their largest size in terms of girth and height away from the road, whereas the corresponding size parameters for the remaining plants were largest at medium distances (500–100 m). However, at up to 20 m, shrubs accounted for higher cover and abundance in comparison to shrubs more distant from the forest edge. In addition, forest edges were characterized by higher species richness and diversity as well as the presence of invasive and expansive species. Similar changes in the tree stand structure were also confirmed by research on the edge effect in a riparian boreal forest [13]. Regarding the tree layer, the research by Borecki et al. [24] also demonstrated a shorter height of the trees at the edge of a forest bordered by a road. Other studies have verified the presence of an ecotone zone in a forest stand near a road that was about 30–100 m wide [25], and the most characteristic physiognomic changes of the stand were found at a distance of 10–15 (20) m from the forest edge. According to other studies [26–30], the most important factors that can affect the edge effect in a forest that is adjacent to an expressway seem to be sunlight, forest management, air and soil pollution, and noise and vibration, which are dependent on the traffic.

We observed a high degree of species migration within the habitat of the forest edge zone, accounting for the unique character of the forest edge, which performs the function of an ecological corridor in which both plant and animal species migrate horizontally. Although we did not analyze traits of plant species present in the forest edge zone, it is believed that wind-pollinated plants and anemochores have a high contribution, while in the interior of a forest, species reproduce and disperse mainly via the zoochoric and barochoric methods [26–28]. In our study, only some wind-dispersed species were more abundant at the forest edge, e.g., *Populus tremula*. In the second case, the range of the spread of the diaspores was limited, and descendants were primarily situated adjacent to the parent organism. However, barochory can also be an introduction to other methods of dispersal [22].

We found that the degrees of change in community composition, which were measured along the edge-to-interior forest gradient, tended to decrease in the interior forest. However, species turnover is determined not only by the distance from the edge of a forest, but also by the degree of human impact that affects the edge of a forest, as well as by the intensity of forest management. Moreover, the value of Whittaker's species turnover can be affected by the types of communities that develop in these two different environments, the deep forest interior and the forest edge zone [20].

A specified value of beta diversity might be a characteristic feature of specific forest communities and might depend on the species composition (e.g., the number of wind-pollinating species (light-seeded shrubs and trees), pioneering species), as well as on the degree of degeneration of the communities (e.g., the number of invasive and expansive species). This analysis showed that the forest areas close to a road are more diversified than we expected. However, forest interiors were more species-rich, as shown by higher values of biodiversity indices.

Our results indicated encroachment by species that occur in the forest edges toward the interior part of a forest. This proves that the edges of the studied forests are constantly under human impact, which affects the species composition in the deep forest. Moreover,

it causes a gradual degeneration and interferes with the succession process. It is worth noting that in the studied forests, we could still observe well-preserved forest interior phytocenoses with no edge-positive species.

The CCA analysis showed a statistically significant distribution of species dependent on the distance from the forest edge. The research showed that along with an increase in the distance from the forest edge, shrub species, which prefer habitats with moderate light and higher trophy (EIV for nitrogen), retreat in favor of shady herbaceous plants and shrubs, which prefer acid soil (EIV for soil reaction). It is important to mention that the composition of a stand is strongly associated with forest management, which in large forest complexes prefers to plant pine stands. Thinning, gradual harvesting, and destructive forms of forest management change the light conditions in forests, thereby enabling the occurrence of species that prefer moderate light such as shrubs.

The variables of slope and aspect turned out to be important factors shaping species composition across transects. More than 75% of plots were flat, whereas the remainder varied between 5–50 degrees of slope. Most were south- and southwest-facing slopes. In the slope forests with southern exposure, the forest edges were formed by alder and riparian forests with a large share of *Padus avium* and *Rubus* sp. The steep slopes in the depths of the forest were overgrown by species with a superficial root system and were associated with an oak-hornbeam habitat. The results indicated that the invasive species *Impatiens parviflora* occurs at the edge of a forest, but that its intrusion into the forest interior zone would be a very unfavorable process for the penetration of the expansive native sedge *Carex brizoides* [31,32].

This study identified a tendency toward the co-incidence of the presence of shrubs and the gradient of soil fertility that is present on the edge of a forest, where the species that prefer an alkaline soil occurred. The occurrence of plants that prefer acidic soil in the forest interior might be caused by the presence of litter, the decomposition of which causes soil acidification [33].

In the forest that is adjacent to an expressway, we found a negative impact from the edge effect on the occurrence of *Vaccinium myrtillus* and *Vaccinium vitis-idea*. The cover of shrubs increased with increasing distance from the forest border adjacent to the expressway. The results of this study are comparable with the results of the studies of Mizera and Grajewski [34] on the impact of expressways on the occurrence of *Ericacea* species.

The abundance of nitrogen contributes to the occurrence of a high density of shrubs at the edge of a forest, which may limit the development of the herb layer due to high shading. However, this enables the development of sciophile forest species and supports the succession process.

Limiting forest management and the formation of a dense layer of shrubs strengthen forest edges, which is necessary for limiting the penetration of alien, invasive, and non-forest species into the deep forest and protecting a specific microclimate. A naturally created forest edge, which is not under human disturbance, might contribute to reducing the fragmentation of forest habitats and might also form new ecological corridors for flora and fauna.

In this study, we found a range of the edge effect at a minimum distance of 0 m from the edge of the forest bordering an expressway. However, this was dependent on the variables that were considered. In the case of shrubs, this was particularly apparent. The results of these studies were similar to the results of research on Czech managed forests, which showed the range of the edge effect from 4 to 18 m from the forest edge [35]. Moreover, other studies have confirmed the presence of the edge effect at a distance of 0–20 m from the edge of a forest, which was determined on the basis of, for example, the plant density in the undergrowth layer [24], tree density [13,36–39], and tree crown and trunk shape [40,41].

The range of the edge effect can also be considered in the context of the presence or absence of a specific correlation between species richness and the distance from the edge of the forest up to 200 m toward the inner zone [11,35,42,43].

An analysis of the edge effect, which considered its impact on the entire biodiversity, not only within plants but also animals, indicated that the edge effect is much larger and might cover an area that can range from 100 m to as much as 1 km from the edge of a forest [44,45].

Our research demonstrated the specificity of forest edges that border expressways and that the edge effect starts approximately 20 m from the forest margin, especially for shrubs. The edge effect can extend even farther into the forest interior in the case of trees. We strongly suggest that the extent of the edge effect be considered when making recommendations for conservation and forest management, because a naturally formed forest edge is important for maintaining biodiversity as well as for mitigating the effects of climate change.

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