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The impact of forest paths upon adjacent vegetation: effects of the path surfacing material on the species composition and soil compaction

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Abstract

This paper describes the vegetation which develops around forest paths (closed to public motor vehicles) in a 4383 ha-beech forest in central Belgium. The main purposes of these investigations were to analyse how far into the forest stands, paths have an influence on the surrounding plant species composition; and to acquire more specific information on the particular effect of some types of surfacing materials. The results show that forest paths have a significant effect on the surrounding plant assemblages. Some species are significantly associated with one particular type of surfacing material. Globally, the presence of a path results in an increase in the number of ruderal species, disturbance indicators, nitrogen-demanding species and indicators of basic conditions. Eutrophication and pH increase, as inferred from the plant composition, are perceptible up to a minimum distance of 10 m from the path. The consequences for long-term conservation of the woodland flora are discussed.

Keywords: Anthropization; Ruderalization; Belt-transect; Road surfacing; Soil compaction

1. Introduction

Road verges, especially grassland vegetation, are interesting landscape elements, according to the still increasing literature devoted to them since the end of the 1960s (e.g. Godefroid, 1999; Godefroid and Tanghe, 2000, 2001; Heindl and Ullman, 1991; Rümler, 1977; Stottele, 1995; Stottele and Schmidt, 1988; Sykora et al., 1993; Tanghe, 1986; Tanghe and Godefroid, 2001; Ullmann et al., 1995, 1998; Ullmann and Heindl, 1989; Way, 1969; Zonderwijk, 1979; Zwaenepoel, 1998). In the beginning of the 20th century, Bates (1935, 1937) already described the vegetation of wayside and footpaths in grassland communities. The observations of Kopecky (1988) revealed a synanthropization of the flora and the vegetation along road verges from non-forested areas in former Czechoslovakia.

The effect of a road upon the environment is complex, and includes disturbance during construction, and pollution both from the road material itself and from the traffic of an established road (Angold, 1997). Considerable research has been carried out on the effects of de-icing salt application on the surrounding environment (e.g. Thompson and Rutter, 1986a,b,c), as well as on the influence of pollutants from vehicle exhausts (Cannon and Bowles, 1962; Chow, 1970; Motto et al., 1970; Munch, 1993), but the influence of foreign materials used in construction into surrounding vegetation has not yet been investigated. Our observations from acidic forest areas in southern Belgium showed that limestone roads may create a locally neutral to alkaline soil in the adjacent community (Godefroid, 1999), but up to now no comparative study has been carried out on the differential effects of various road surfaces. Numerous studies have documented the effect of dolomite on forest soils (e.g. Dulière et al., 1999; Hultberg et al., 1995; Meiwes et al., 2002; Nilsson et al., 2001; Ponette et al., 1997), but few studies have considered dolomite as a road material. Effect of road building on the hydrology

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of surrounding areas has been widely studied (La Marche and Lettenmaier, 2001; Rummer et al., 1997; Tague and Band, 2001; Ziegler and Giambelluca, 1997), and detailed studies also exist on sediment production from forest roads (Appelboom et al., 2002; Costantini et al., 1999; Fransen et al., 2001; Kahklen, 2001; Luce and Cundy, 1994; Luce and Black, 1999; Reid and Dunne, 1984; Rummer et al., 1997). Most of these studies, however, concern the impacts of road sediments on downstream aquatic ecosystems. The possible effects of different road surfaces on surrounding vegetation are still unexplored.

This paper describes the vegetation which develops around forest paths in an ancient beech forest in central Belgium. An essential aim was to determine the role of path surfacing in the sustainable management of forests. The purpose of these investigations was twofold: (1) to analyse how far into the forest stands the paths have an influence on the surrounding plant species composition; and (2) to acquire more specific information on the particular floristic effect of each type of path covering.

2. Study area

The research was conducted in the Sonian Forest, south of Brussels (50°47′N; 4°26′E). This area has been proposed as a Site of Community Importance (Natura 2000 area, in fulfilment of the EC-Habitat Directive 92/43/EEC). It is a remnant of the huge forest that is supposed to have covered the whole of Western Europe after the last Ice Age. The forest actually covers an area of 4383 ha, 1654 ha of which are situated within the administrative limits of the Brussels Capital Region, this constituting a management unit and being the area taken into consideration in the present study. Some 20000 years ago, sandstone and flintstone formed the upper layer in the area of the Sonian Forest. After the last Ice Age, this layer was covered with loess. Today, almost the whole surface of the forest (95%) is composed of a 3–4 m thick silt layer, which corresponds to the loess deposition (Langohr and Cuyckens, 1986). The forest ranges in altitude from 65 to 130 m a.s.l. The climate of the area is temperate and humid, with a growing season of 7 months (April–October). Mean annual temperature is 9.9 °C, annual precipitation is 798 mm (Lieth et al., 1999). The natural vegetation is a deciduous forest in which oaks (*Quercus robur* and *Quercus petraea*) and beech (*Fagus sylvatica*) are the main species (Herbauts et al., 1996). Since the plantation work of the Austrian administration at the end of the 18th century, it is now composed of 74% of beech trees (*Fagus sylvatica*). Except beech, few other woody species are found. Sixteen percent of the forest surface is occupied by oak stands (*Quercus robur*) and 8% is represented by stands of introduced conifers (*Pinus sylvestris*, *Larix decidua*, *Picea abies*) (Vanwijnsberghe, 2000). The study site chosen is particularly representative of the surfacing methods and materials used for that area. The road and path network is extremely dense. The distribution of the surface types used is given in Table 1.

Table 1
Length and density of the different path surfacing materials used in the Sonian Forest (data from Vanwijnsberghe, 2000)

Surfacing material	Length (m)	Density (m/ha)
Asphalt	22,670	13.71
Concrete	3740	2.26
Cobblestones	4035	2.44
Dolomite	90,470	54.70
Sand	19,046	11.52
Total	139,961	84.62

3. Methods

3.1. Choice of sampling areas

Compaction is strongly related to the original bulk density, forest type and soil parent material (Williamson and Neilsen, 2000). So, sampling areas were to observe certain prerequisites: (1) same soil type; the prevailing soil type with an Abc profile was chosen (USDA: Hapludalf and Glossudalf; FAO: Luvisols and Podzoluvisols; French classification: Sols lessivés, Sols lessivés hydromorphes and Sols lessivés à pseudogley); (2) same topography (i.e. horizontal); (3) same overstory species (i.e. beech stands), as tree species can also change the distribution of pore sizes in soils (Nihlgard, 1971), and (4) same traffic intensity and vehicle characteristics (i.e. roads closed to public motor vehicles but accessible for foresters vehicles). As there is a significant positive correlation between soil compaction and stand age (Godefroid and Koedam, 2004), stands were chosen with ages as different as possible (planted between 1815 and 1969), in order to have a broad range of compaction values. A map of the areas meeting these conditions was drawn by overlaying the soil map and the stand map of the whole forest in the G.I.S. Arc View (ESRI, 1996).

3.2. Vegetation sampling

Within these pre-defined areas, 50 10 m-belt transects were randomly laid out for vegetation sampling and soil compaction measurements. Five types of path surfaces were taken into consideration in the framework of this study, i.e. asphalt, bare soil (native forest soil), dolomite, cobblestones and sand (concrete was not included in the sampling design because it did not exactly meet the previously mentioned criteria). For each type of path surface, ten transects were carried out. Along each transect, ten 10 m^2-quadrats (10 m × 1 m) were laid out

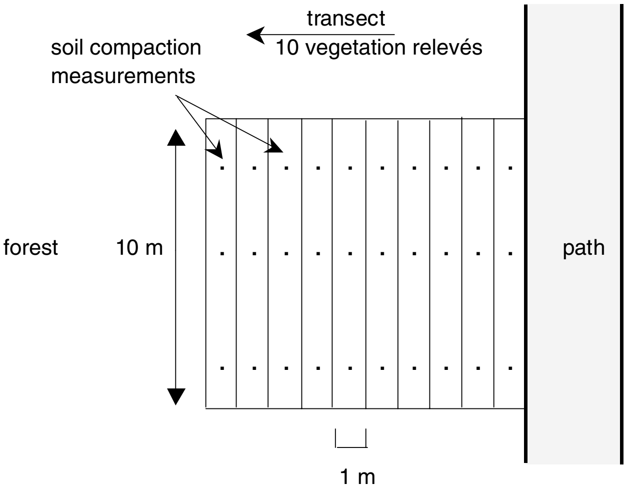

Fig. 1. Diagram showing the sampling design used for the study of vegetation and soil compaction in the surroundings of forest paths.

next to each other (Fig. 1). In each quadrat, the species composition was characterized by classical phytosociological relevés according to the Braun–Blanquet method (e.g. Westhoff and van der Maarel, 1973).

3.3. Recording of soil compaction

In each of the 500 sample plots, three measurements of soil compaction equidistant of 3 m (Fig. 1) were recorded using a cone-penetrometer (Eijkelkamp Agrisearch Equipment, The Netherlands), a device forced into the soil to measure its resistance to vertical penetration. The average value was taken for statistical analyses. The penetrometer has a 60° cone-shaped tip. According to the soil strength, three tips were used (1–2 cm diameter). When the tip is pushed into the soil, the penetrometer provides a continuous plotting of soil strength and soil depth, unless impenetrable stone or wood is encountered (Miller et al., 2001). The readings are expressed in newton (N), the SI unit of force. Measurements were performed up to 20 cm depth, as a 0–20 depth range is usually used in the literature (Brevik et al., 2002; Carman, 2002; Servadio et al., 2001) and because it permitted to avoid the natural compaction beginning at 40 cm depth in the Sonian Forest. Cone penetrometers are frequently used to measure soil resistance (e.g. Jansson and Wasterlund, 1999; Seixas and McDonald, 1997). Because of the relative ease of conducting in situ compaction tests, this method was chosen as an attractive alternative for field compaction studies. Furthermore, Dawidowski et al. (2001) highlighted that measuring soil compaction strength in situ with a portable penetrometer was statistically similar to traditional laboratory compression tests of soil cores.

Because penetrometer readings can be strongly dependent on soil moisture content (Miller et al., 2001; Vaz et al., 2001), field samplings were carried out in spring when soils are near field capacity so that penetrometer readings are least influenced by differences in soil moisture (Miller et al., 2001).

3.4. Data analyses

In order to detect the patterns of variation in the species data that can be explained by environmental variables, we calculated a constrained ordination (CCA; Ter Braak and Gremmen, 1987) using Canoco 4.0 for Windows (Ter Braak and Šmilauer, 1998). Since Braun–Blanquet cover-abundance values are not suitable for mathematical treatment, raw data were transformed by taking the median of each scale interval: 87.5; 62.5; 37.5; 15; 2.5; 0.5 and 0.2, accounting respectively for 5; 4; 3; 2; 1; + and r (arbitrary values were taken for r, + and 1). Five explanatory variables were categorical variables, representing the path surface. The other five were quantitative (soil compaction, as well as inferred moisture, light, reaction and nitrogen index). These were estimated using Ellenberg's indicator values which have been widely employed and validated for the interpretation of the variation among plant communities in space and time in many northern European countries (e.g. Diekmann and Dupré, 1997; Persson, 1981; Ter Braak and Gremmen, 1987; van der Maarel, 1993). Because species are not always constant in their ecological requirements and ought in principle to have different indicator values in different parts of their range (Hill et al., 1999), we used the recalibrated Ellenberg's indicator values for the British Isles (phytogeographically closer to our study area), instead of the original ones which were defined for Central Europe (Ellenberg et al., 1991). Weighted averages of Ellenberg's indicator values (mIV) were calculated for each sample using the following equation:

$$\mathrm{mIV} = \frac{(x_1\mathrm{IV}_1 + x_2\mathrm{IV}_2 + \cdots + x_n\mathrm{IV}_n)}{(\mathrm{IV}_1 + \mathrm{IV}_2 + \cdots + \mathrm{IV}_n)}, \qquad (1)$$

where $x_1, x_2, \ldots, x_n$ are the cover-abundance values of those species present in the relevé, and $\mathrm{IV}_1, \mathrm{IV}_2, \ldots, \mathrm{IV}_n$ represent Ellenberg' indicator values, either nitrogen (mN), moisture (mF), reaction (mR) or light (mL).

Indicator species for each path surface and distance to the path were derived by the method of Dufrêne and Legendre (1997), as available in the PC-ORD package (McCune and Mefford, 1997). The method combines information on the concentration of species abundance in a particular group and the faithfulness of occurrence of a species in a group. It produces indicator values for each species in each group, which are tested for statistical differences using a Monte Carlo technique (Dufrêne and Legendre, 1997).

To evaluate the possible influence of forest paths upon adjacent vegetation, we used Analyses of Variance followed by Student Newman–Keuls tests (predictor variables: path surface and distance from path) on the species richness of particular functional ecological plant species groups throughout the transects.

Forest species and disturbance species are determined according to Stieperaere and Fransen (1982). C-S-R strategies were obtained from Grime et al. (1988). Intermediate strategies were pooled according to Graae and Sunde (2000) using the following categories:

C+ (competitors): C, C/CR, C/CSR, C/SC

CSR+ (competitive and stress-tolerant ruderals): CR, CR/CSR, CSR, SC, SC/CSR, SR, SR/CSR

R+ (ruderals): R, R/CR, R/CSR, R/SR

S+ (stress tolerants): S, S/CSR, S/SC, S/SR

Seed bank persistence was obtained from the extensive database of Thompson et al. (1997): (1) transient (<1 yr); (2) short-term persistent (> 1 < 5 yr); (3) long-term persistent (>5 yr).

If not stated otherwise, all statistical analyses were carried out with Statistica Version 6.0 (Statsoft Inc., 2001). The 0.05 level of probability was accepted as significant throughout the work.

Nomenclature and species life forms are given by Lambinon et al. (1998). The highly variable and taxonomically disputed *Rubus fruticosus* s.l. was considered a single species.

4. Results

The arrangement of the 500 quadrats in the CCA ordination is shown in Fig. 2. Eigenvalues of first and second axis were 0.278 and 0.166, respectively. Table 2 shows the variance explained by each of the variables tested and the cumulative variance explained. The variance explained by all variables is 82%. They all explained significant ($P < 0.05$) amounts of variation in the species data: soil reaction index is the best predictor (27%), followed by soil nitrogen index (12%) and light index (11%). The canonical correspondence analysis indicates therefore that patterns of variation in the species data can be explained by road surface. Species scores illustrate taxa typical on cobblestones and bare soils in the lower left and right sides of Fig. 2, those most frequent on dolomite, asphalt and sand in the upper left and right sides of the diagram. *Dryopteris dilatata* shows a strong bias for stands associated with non-surfaced paths. *Impatiens parviflora*,

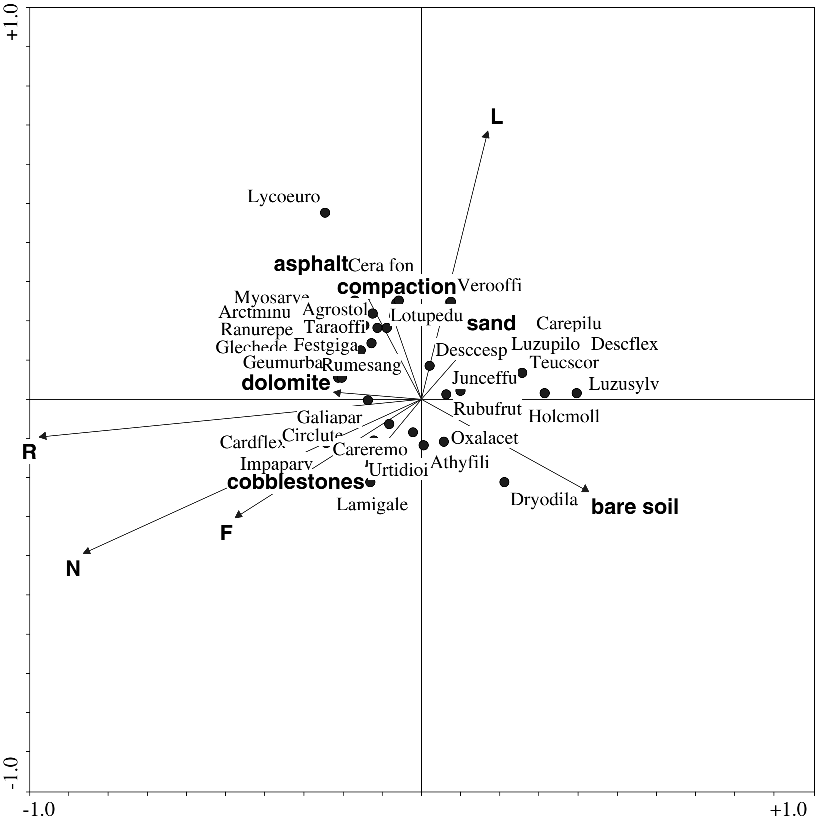

Fig. 2. Species ordination diagram based on canonical correspondence analysis with respect to five quantitative variables (light (L), moisture (F), nitrogen (N), reaction (R) indices, and soil compaction) represented by arrows and five nominal variables (asphalt, bare soil, dolomite, cobblestones, sand) shown by their centroid. The axes (1: horizontal; 2: vertical) are scaled in standard deviation units. Species abbreviations are based on the first four letters of the genus and the species.

Table 2
Percentage variation explained by explanatory variables and level of significance (Monte Carlo test)

Explanatory variable	Variance explained by single variable (%)	Cumulative variance explained (%)	*P*-level
soil reaction index (**R**)	27	27	0.0050
soil nitrogen index (**N**)	12	39	0.0050
light index (**L**)	11	50	0.0050
Bare soil	7	57	0.0050
Cobble stones	7	64	0.0050
soil moisture index (**F**)	5	69	0.0050
Asphalt	5	74	0.0050
soil compaction	4	78	0.0050
Dolomite	4	82	0.0050

Abbreviations for environmental variables indicated by bold-face letters.

Lamium galeobdolon and *Urtica dioica* are more frequent in the vicinity of cobblestone roads. The presence of *Myosotis arvensis*, *Plantago major*, *Lycopus europaeus* seems to be correlated to asphalted paths. The close positioning of *Veronica officinalis* and *Carex pilulifera* near the sand centroid indicates that these species have a strong preference for this surfacing method. Table 3 gives the indicator value for significant indicator species for each path surface and for each measured distance to the path. It appears that there are very few indicators of the inner forest in comparison with the great amount of species which were found to be typical of plots nearby the paths. Among the latter, *Agrostis stolonifera*, *Geum urbanum*, *Plantago major*, *Poa annua*, *Polygonum hydropiper*, *Prunella vulgaris*, *Rumex sanguineus*, *Stellaria media*, *Taraxacum officinale* and *Trifolium repens* are the best indicators of plots located within a very short distance (maximum 1 m) from the path, and this whatever the type of surfacing method used. Other indicator species of the same distance show a clear preference for only one surface type, e.g. *Carex ovalis*, *Juncus tenuis*, *Lotus pedunculatus* or *Lysimachia nemorum* which are typically associated with bare paths (native soil). *Brachypodium sylvaticum*, *Carex sylvatica*, *Geranium robertianum*, *Juncus effusus* and *Lapsana communis* are indicators of asphalted paths, while *Carex remota*, *Cerastium fontanum* and *Festuca gigantea* systematically avoid the vicinity of this surfacing. Species which avoid the proximity of paths, i.e. which are more or less restricted to the inner forest, are *Carex pilulifera*, *Dryopteris dilatata* and *Luzula pilosa*.

Table 4 gives the global variation of plant traits and environmental variables along the transects from the path into the forest (all path types together). Among the 17 parameters we examined, 14 did significantly vary according to the distance from the path. The mean proportion of forest species increases as one moves away from the path. The opposite pattern is found for the disturbance species. Soil reaction and soil nitrogen indices gradually decrease along the transects. The same trend is found for the soil moisture index but with a narrower amplitude. Competitive and stress-tolerant species increase, while ruderals strongly decrease throughout the transects. Geophytes and therophytes are less represented in the inner forest and the same happens for short-term persistent, long-term persistent and transient seeds. Mean soil compaction level decreases up to a distance of 4 m from the path. Light index, competitive and stress-tolerant ruderals, and hemicryptophytes did not significantly vary along the transects. These results are graphically expressed in Figs. 3 and 4 for each path surface separately. For most of the plant traits and for soil compaction, the paths exert an influence extending until a distance of 3–4 m inside the forest. However, for soil reaction and soil nitrogen indices, the effect of the path is still present at a distance of 10 m inside the forest.

The global influence (without distance effect) of the path surface on the species composition and environmental conditions is shown in Figs. 5 and 6. Forest species and geophytes are better represented in the surroundings of cobblestone paths. Therophytes and short-term persistent species are favoured by asphalt and dolomite covering in the vicinity, while transient species are more numerous along asphalt and dolomite. Likewise, disturbance species show a preference for asphalt covering, but they are also favoured by paths covered by sand or without surface (bare soil). Competitive species grow better close to sand or bare paths. Ruderals are better represented in the surroundings of paths covered by asphalt, dolomite or sand.

5. Discussion

5.1. Path influence on the surrounding plant composition

These results show that forest paths have a significant effect on the surrounding plant assemblages. Globally, the presence of a path results in an increase in the amount of ruderal species, disturbance indicators, nitrogen-demanding species and indicators of basic conditions. Furthermore, soil compaction has been found to be higher in the vicinity of forest paths. These effects may be due to either path construction (initial impact) or some kind of pollution (contamination) from the surface material itself of an established path (recurrent impact). We remind that there is no motorized traffic on the sampled paths (foresters' vehicles are very occasionally), so that we can consider that there is no pollution from the traffic. Even for forest paths, the construction phase

Table 3
Indicator values for significant ($P < 0.05$) indicator species as identified by the method of Dufrêne and Legendre (1997) for each path substrate and distance to the path

	1m					2m					3m					4m					5m					6m					7m					8m					9m					10m				
	A	B	D	C	S	A	B	D	C	S	A	B	D	C	S	A	B	D	C	S	A	B	D	C	S	A	B	D	C	S	A	B	D	C	S	A	B	D	C	S	A	B	D	C	S	A	B	D	C	S
Agrostis stolonifera	37.4	69.1	38.4	58.1	31.5		36.1																																											
Arctium minus	54.8		48.9	25.5		32.7																																												
Athyrium filix-femina							59.0		54.8	53.5														58.8																										
Brachypodium sylvaticum	23.5					31.4		18.0																																										
Cardamine flexuosa	27.9		59.3	26.6	18.0																																													
Cardamine hirsuta				50.0																																														
Carex ovalis		26.3																																									26.6							
Carex pilulifera	40.4				46.7																										46.6							50.4				47.2	41.1					52.5		46.9
Carex remota		60.2	57.4	62.3	68.3																																													
Carex strigosa	25.0		38.9																																															
Carex sylvatica	34.8									18.9																																								
Cerastium fontanum		26.1	36.0	25.9	24.2																																													
Circaea lutetiana					73.5			59.5	62.0	69.6	62.8		59.5	58.7	58.3	53.1		59.5																	50.3								57.9		51.9			63.8		
Cirsium arvense					19.3			30.6																																										
Cirsium vulgare					19.6																																													
Deschampsia cespitosa						57.3																																												
Deschampsia flexuosa																																																37.2		
Dryopteris dilatata															42.2														40.1									48.5					47.5			36.7		52.5		
Epilobium montanum					18.9								18.6																																					
Epilobium parviflorum																		18.0																																
Festuca gigantea		26.1	44.4	49.1	34.7	41.7			43.2																																									
Galium aparine						53.8		51.4																																										
Geranium robertianum	25.0																																																	
Geum urbanum	69.9	18.9	80.5	81.0	45.0	47.8		63.4			46.6		58.6																							42.7					42.7		52.2			42.7		52.2		
Glechoma hederacea					18.8																																													
Impatiens parviflora	56.3	47.8		59.4			49.6																																											
Juncus conglomeratus																																											18.0							
Juncus effusus	52.9																																					50.0												
Juncus tenuis		43.4																																																
Lapsana communis	37.9																																																	
Lotus pedunculatus		27.5							20.0																																									
Luzula multiflora																												30.0			34.2																			
Luzula pilosa																																				44.2	24.5	49.9												
Luzula sylvatica																										30.9																								
Lysimachia nemorum		16.9																																																
Myosotis arvensis					27.5																																													
Oxalis acetosella																									47.6																									
Plantago major	44.5	60.0	65.2	88.3	17.3																																													
Poa annua	74.3	93.7	83.2	83.2	80.3																																													
Poa nemoralis			18.6																																															
Poa trivialis	56.5				56.8			27.9																																										
Polygonum hydropiper	35.0	82.5	64.9	74.3	52.8					28.1																																								
Prunella vulgaris	36.0	38.4	61.1	76.6	42.2			41.9																																										
Ranunculus repens	50.5		54.0	34.8	26.3	54.0																																												
Rubus fruticosus				61.4																																														
Rubus idaeus							35.2																																											
Rumex sanguineus	73.2	27.8	69.5	66.3	54.4	65.3		47.5			48.3		51.4																												41.6							44.4		
Scrophularia nodosa		40.9		60.0																																														
Stellaria alsine		28.9		40.0																																														
Stellaria media	20.0	60.0	44.4	70.0	48.9																																													
Taraxacum officinale	74.2	20.0	52.9	30.5	54.8	31.5																																												
Trifolium repens	27.4	20.0	29.0	29.5	18.6																																													
Urtica dioica		55.6	58.3		66.1	50.5	58.1	63.8		58.7				66.2	46.7																												54.2	54.9				60.4	52.8	
Veronica montana			37.3	48.8																																														
Veronica officinalis													30.0																																					
Veronica serpyllifolia		30.0	37.9	50.0																															18.0															

A: asphalt; B: bare soil; D: dolomite; C: cobblestones; S: sand.

Table 4
Mean values (+SE) of environmental variables along the transects from the path into the forest (one-way ANOVA followed by a Student Newman–Keuls test)

	p-level		Distance to the path									
			1 m	2 m	3 m	4 m	5 m	6 m	7 m	8 m	9 m	10 m
Forest species (%)	0.0005	Mean	40.94	49.98	50.94	52.95	54.84	55.76	49.76	53.39	50.44	51.41
		SE	1.60	1.90	1.85	1.85	2.08	2.36	2.27	2.62	2.75	2.70
Disturbance species (%)	<0.0001	Mean	27.98	16.25	14.44	13.99	13.22	13.93	14.44	12.75	14.64	11.77
		SE	1.22	1.42	1.44	1.40	1.37	1.46	1.50	1.40	1.79	1.44
Light index (ml)	NS	Mean	5.44	5.41	5.39	5.41	5.47	5.50	5.48	5.47	5.51	5.59
		SE	0.08	0.07	0.07	0.08	0.07	0.07	0.08	0.08	0.08	0.08
Soil moisture index (mF)	0.0152	Mean	6.25	6.12	6.03	5.94	5.96	5.95	5.98	5.99	6.00	5.95
		SE	0.06	0.05	0.04	0.06	0.06	0.06	0.08	0.07	0.07	0.08
Soil reaction index (mR)	<0.0001	Mean	6.25	6.10	5.89	5.68	5.49	5.43	5.34	5.20	5.11	4.94
		SE	0.06	0.09	0.11	0.14	0.12	0.11	0.11	0.12	0.13	0.13
Soil nitrogen index (mN)	<0.0001	Mean	6.22	6.20	5.93	5.68	5.52	5.45	5.32	5.17	5.16	5.05
		SE	0.09	0.12	0.13	0.15	0.14	0.14	0.13	0.13	0.14	0.14
C+	<0.0001	Mean	11.31	17.65	20.31	20.77	20.31	22.11	22.17	22.63	22.69	23.77
		SE	0.81	1.12	1.26	1.47	1.33	1.46	1.41	1.48	1.82	1.64
S+	0.0355	Mean	11.89	15.85	16.62	17.64	19.10	20.01	13.94	17.04	15.26	14.44
		SE	1.02	1.33	1.28	1.69	2.02	2.37	1.62	1.84	1.94	1.65
R+	<0.0001	Mean	18.51	7.54	4.49	4.22	4.29	2.87	2.68	1.99	4.50	2.36
		SE	0.86	1.03	0.81	0.90	0.84	0.70	0.72	0.59	1.36	0.77
CSR+	NS	Mean	31.32	33.76	33.34	35.06	34.54	33.22	34.16	33.74	33.12	35.99
		SE	1.22	1.25	1.24	1.23	1.55	1.89	1.74	2.12	1.73	1.83
Geophytes (%)	0.0186	Mean	6.15	8.55	8.92	8.12	6.81	7.40	6.37	6.21	5.66	6.39
		SE	0.47	0.60	0.68	0.74	0.72	0.77	0.84	0.80	0.81	0.99
Hemicryptophytes (%)	NS	Mean	61.74	64.35	64.85	65.03	64.97	66.96	64.16	66.67	65.23	66.56
		SE	1.03	1.27	1.42	1.56	1.63	1.82	2.19	2.35	2.59	1.98
Therophytes (%)	<0.0001	Mean	23.37	16.04	14.09	13.68	13.53	10.43	10.63	8.63	11.56	9.41
		SE	1.04	1.19	1.19	1.27	1.38	1.27	1.28	1.33	1.84	1.42
Short-term persistent seeds (%)	<0.0001	Mean	8.65	7.93	7.84	7.07	5.93	4.79	5.49	4.36	3.94	3.91
		SE	0.76	0.86	0.89	0.95	0.75	0.81	0.82	0.66	0.77	0.73
Long-term persistent seeds (%)	<0.0001	Mean	34.38	24.57	22.14	20.59	20.05	19.70	18.59	17.68	19.94	19.05
		SE	1.29	1.44	1.11	1.46	1.53	1.50	1.57	2.12	2.25	1.19
Transient seeds (%)	<0.0001	Mean	12.68	14.29	12.55	12.09	9.77	8.31	7.42	6.72	7.17	7.57
		SE	0.81	0.98	1.15	1.32	1.24	1.14	1.09	1.11	1.22	1.22
Soil compaction (N)	<0.0001	Mean	490.01	386.79	327.57	323.01	346.63	348.58	343.63	359.37	357.81	358.65
		SE	21.69	22.87	21.34	20.16	20.02	18.65	17.73	18.56	17.95	15.93

NS: no significant differences.

involves the use of heavy machinery and standard processing such as tree clearing, shaping of the roadbed, allowing for drainage, etc. This initial phase accounts for the disappearance of the most vulnerable species and the development of plants adapted to this kind of disturbance, and can also explain the increase in soil compaction on both sides of the forest path. This is also in accordance with the results of Angold (1997), who investigated in UK the effect of a road on adjacent heathland vegetation, and found that there was an increase in the abundance of grasses in the vegetation near roads. This author attributed this pattern to the changes in relative competitive ability of plant species under conditions of eutrophication. This phenomenon might be produced by the contamination from the surface material itself, as illustrated by the patterns observed in this study, highlighting a significant difference between non-covered and covered paths, particularly for

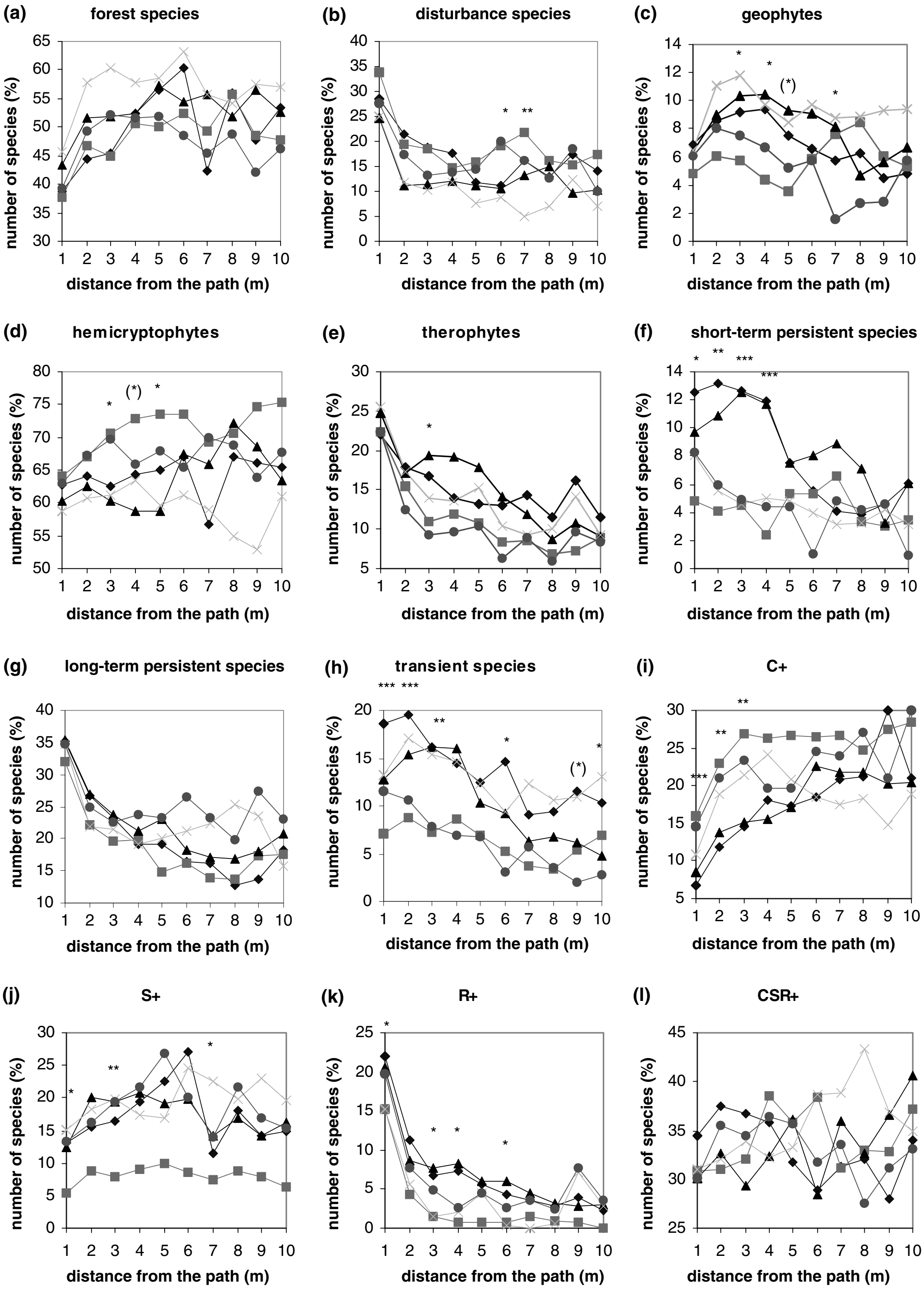

Fig. 3. Spatial evolution of plant traits along transects from the path into the forest for each surface separately. (a) forest species; (b) disturbance species; (c) geophytes; (d) hemicryptophytes; (e) therophytes; (f) short-term persistent species; (g) long-term persistent species; (h) transient species; (i) competitors (C+); (j) stress tolerants (S+); (k) ruderals (R+); (l) competitive and stress-tolerant ruderals (CSR+). Diamonds: asphalt; squares: bare soil; triangles: dolomite; crosses: cobblestones; circles: sand. Asterisks show significant differences within each distance according to an ANOVA (***: $P < 0.001$; **: $P < 0.01$; *: $P < 0.05$).

indicators of basic reaction and for nitrogen-demanding species. The associated flora or environmental variables did however not show the same response according to the surface type. For instance, the mean soil nitrogen index was significantly higher with dolomite and cobblestones than for asphalt and sand. This is in agreement with re-

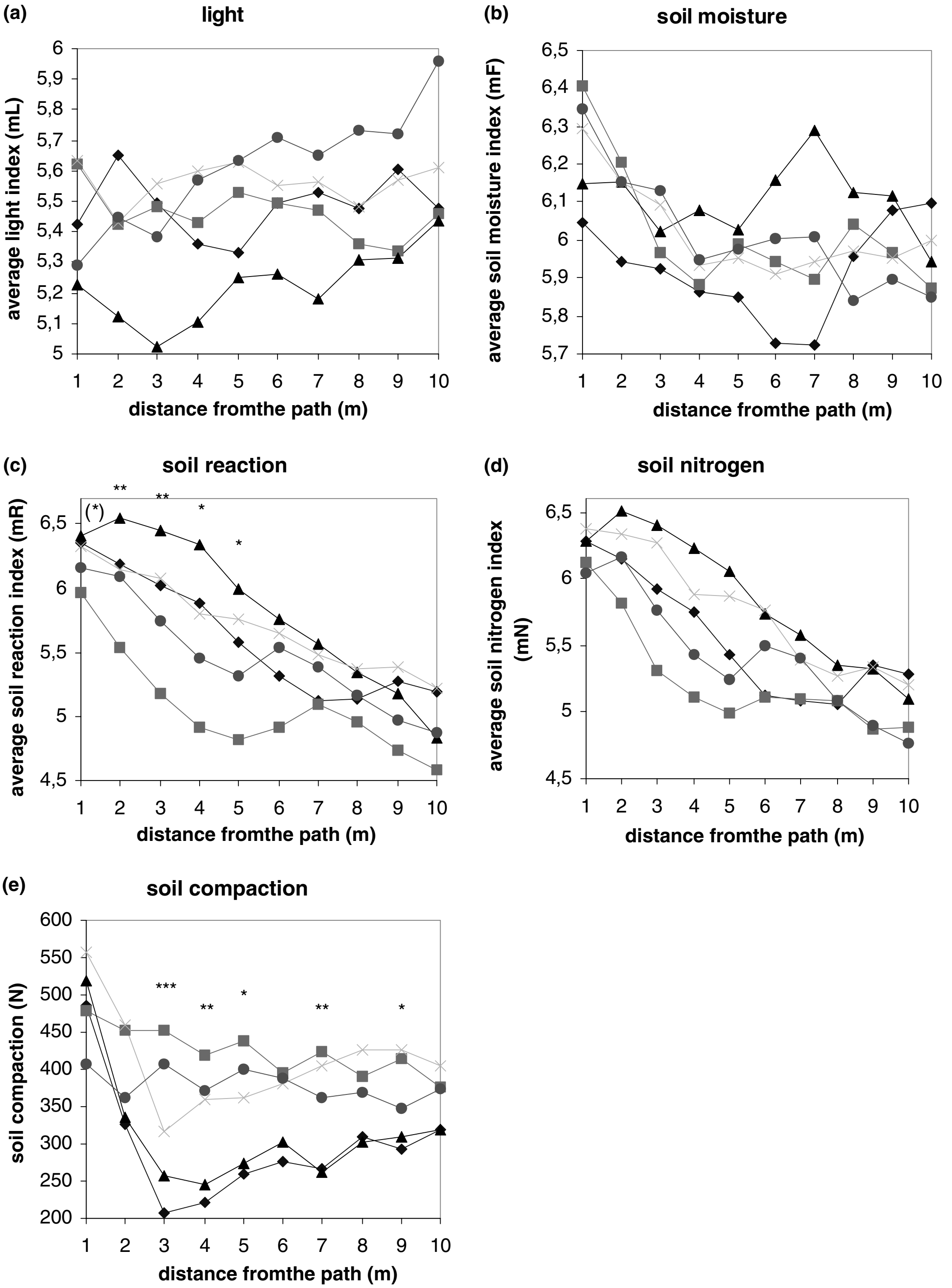

Fig. 4. Spatial evolution of environmental variables along transects from the path into the forest for each surface separately. (a) light; (b) soil moisture; (c) soil reaction; (d) soil nitrogen; (e) soil compaction. Diamonds: asphalt; squares: bare soil; triangles: dolomite; crosses: cobblestones; circles: sand. Asterisks show significant differences within each distance according to an ANOVA (***: $P < 0.001$; **: $P < 0.01$; *: $P < 0.05$).

sults of Dulière et al. (1999) showing that dolomite lime is responsible of the appearance of N-demanding species. In our study area, it becomes clear that the surfacing material used for forest paths has a significant effect on the eutrophication of the surrounding forest environment. This may happen via a lateral sedimentation process, as highlighted for other forested areas by Appelboom et al. (2002), who have observed that the predominant source of sediment is from the construction and maintenance of access roads, which contribute as much as 90% of the total eroded sediments. Variables associated with sediment production are road

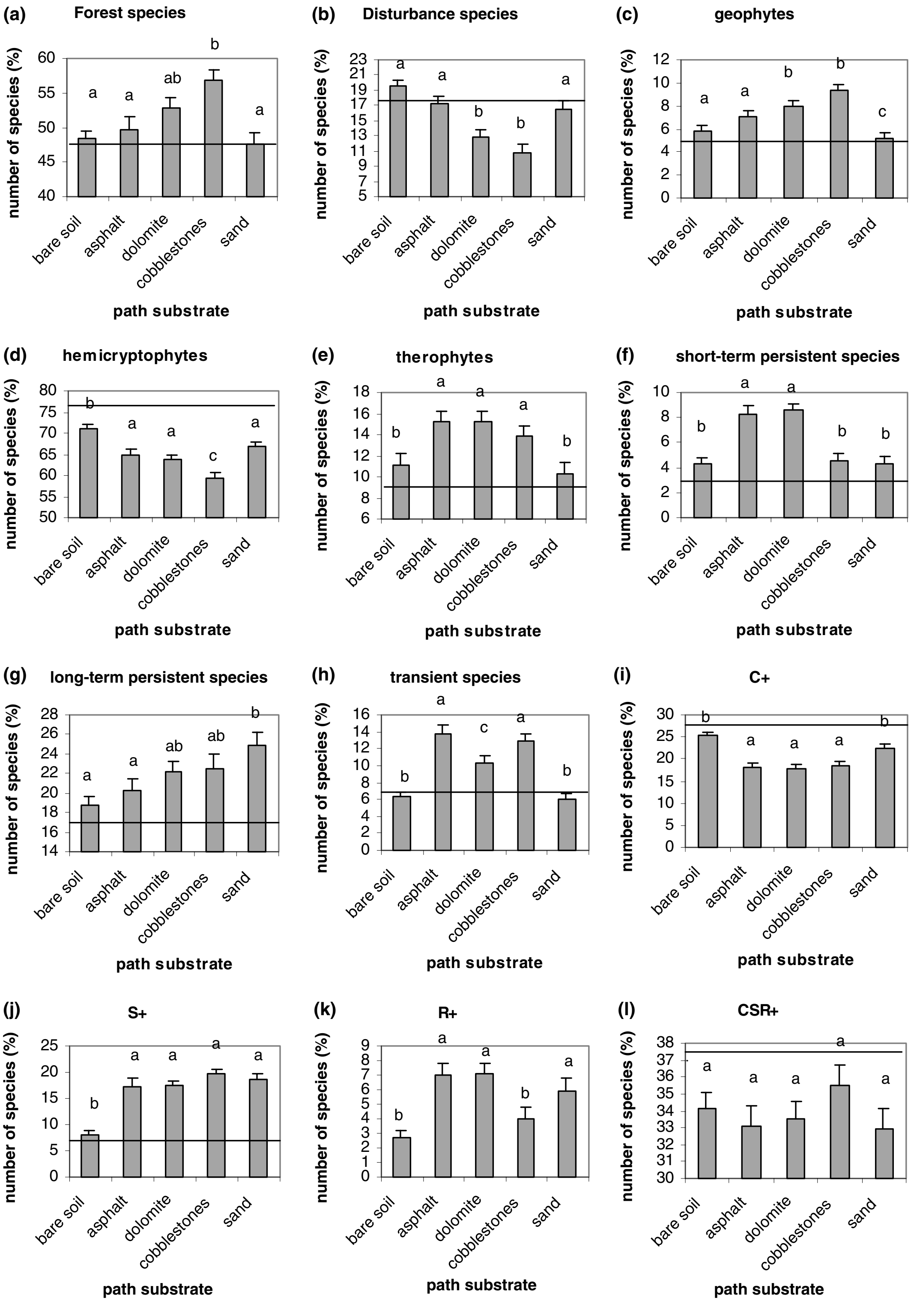

Fig. 5. Mean values (+SE) of species numbers (%) along five path surfaces. (a) forest species ($F = 5.72$; df 4, 495; $P = 0.0002$); (b) disturbance species ($F = 10.78$; df 4, 495; $P < 0.0001$); (c) geophytes ($F = 10.34$; df 4, 495; $P < 0.0001$); (d) hemicryptophytes ($F = 12.73$; df 4, 495; $P < 0.0001$); (e) therophytes ($F = 5.24$; df 4, 495; $P = 0.0004$); (f) short-term persistent species ($F = 15.64$; df 4, 495; $P < 0.0001$); (g) long-term persistent species ($F = 3.97$; df 4, 495; $P = 0.0035$); (h) transient species ($F = 21.13$; df 4, 495; $P < 0.0001$); (i) competitors (C+) ($F = 10.96$; df 4, 495; $P < 0.0001$); (j) stress tolerants (S+) ($F = 16.39$; df 4, 495; $P < 0.0001$); (k) ruderals (R+) ($F = 6.73$; df 4, 495; $P < 0.0001$); (l) competitive and stress-tolerant ruderals (CSR+) ($F = 0.79$; df 4, 495; NS). Differing letters indicate significant differences using a one-way ANOVA followed by a Student Newman–Keuls test. Horizontal lines indicate average values found at a distance of 10 m from non-covered paths (bare soil); for ruderal species is this value equal to zero.

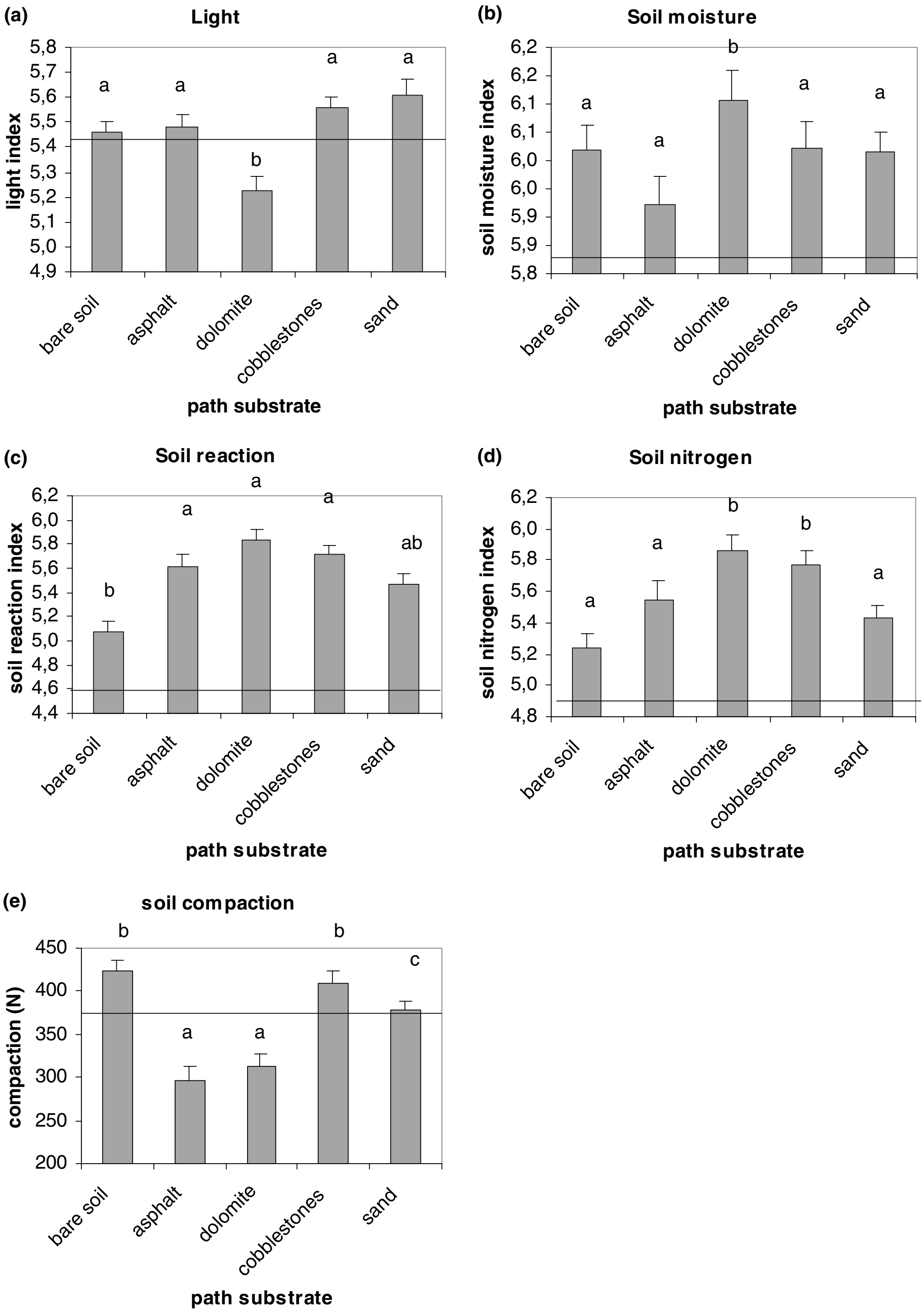

Fig. 6. Mean values (+SE) of environmental variables along five path surfaces. (a) light ($F = 8.23$; df 4, 495; $P < 0.0001$); (b) soil moisture ($F = 2.02$; df 4, 495; NS); (c) soil reaction ($F = 12.21$; df 4, 495; $P < 0.0001$); (d) soil nitrogen ($F = 6.19$; df 4, 495; $P < 0.0001$); (e) soil compaction ($F = 17.78$; df 4, 495; $P < 0.0001$). Differing letters indicate significant differences using a one-way ANOVA followed by a Student Newman–Keuls test. Horizontal lines indicate average values found at a distance of 10 m from non-covered paths (bare soil).

surfacing material, construction method, age, precipitation (Kahklen, 2001), traffic intensity and vehicle characteristics (Bilby et al., 1989; Reid and Dunne, 1984). The last four variables do not sufficiently vary in our study area to account for differences in sediment production. The evidence that sediment production is different according to different surfacing materials was recently provided by the study of Costantini et al. (1999)

on the erosion and sediment transport for a range of forest road surfaces, which revealed very low concentrations of fine particles in the surface of gravel roads, and somewhat higher proportions in ungravelled (dirt) road surfaces. In the work of Luce and Black (1999), sediment production from aggregate covered roads on a silty clay loam was about 9 times greater than that from roads constructed on a gravelly loam. This sediment production may also be considered as responsible for the increase in the number of indicators of basic reaction found on both sides of surfaced forest paths. As dolomite contains a substantial quantity of bases, we would have expected a significantly higher soil reaction index in the surroundings of dolomite when compared to other surfacing materials. But surprisingly, our results did not show this pattern. This is probably due to the fact that the other surfacing materials studied may also release a certain quantity of Ca ions depending on the origin of the sand or the nature of the cement used for fixing cobblestones. It must also been noted that dolomite does not always release a lot of ions such as observed by some authors. Holmberg et al. (2000) studied the leaching characteristics of granules made of dolomite and they found that the release of Ca and Mg was low, 1–5% during 7 months. Ponette et al. (1997) also showed, in a reconstructed acid brown forest soil profile, that downward movement of Ca and Mg ions from dolomite was very limited. The lower light index and the higher soil moisture index associated with dolomite-surfaced paths are much more difficult to explain. The cause is unknown for light, while for moisture one possibility may be that the draining effect would be more efficient with dolomite than with other surface types. The higher compaction level found in the vicinity of bare soils and sand-covered paths when compared to asphalt and dolomite surfaces can be explained by the fact that those paths are less clearly delimited, so that visitors (e.g. walkers, riders, bikers) easily go beyond the physical limits of the paths.

Other plant functional groups (e.g. disturbance indicators, therophytes, transient species) did also show a different response according to the surfacing material. Because these functional groups do normally not show a clear link with nutrient enrichment, we assume that their differential behaviour might actually be due to the damage caused by the construction method rather than the surfacing material per se, which is in agreement with Kahklen (2001).

According to Kahklen (2001), two main processes may be involved in the spread of the sediments in the path vicinity: (1) the road surface materials are reduced to a transportable size because of foresters vehicles, joggers, riders and walkers, who break down surfacing material resulting in finer surface gradation and increased sediment transport from the road surface; (2) fine particles are easily eroded from the road surfacing during precipitation events. How easily and in what proportion it happens, will depend on the type of surfacing material used. Hard or coarse materials would normally be less subjected to sediment transport than crumbly materials with fine particles. This theoretical pattern however does not appear so clearly in our results, as we did not find a longer distance effect for native soils (silt) or sand-covered paths, when compared with asphalt, dolomite and cobblestones. Distance effects were almost the same for all surfacing materials, and are reduced to 3–4 m from the path bed for all plant functional groups except two, nitrogen-demanding species and indicators of higher pH. Eutrophication and pH increase, as inferred from the plant composition, are perceptible up to a minimum distance of 10 m from the path. These patterns are similar to those found in a subtropical forest in Puerto Rico, where Olander et al. (1998) studied the impact of disturbance initiated by road construction. They found that the road has little effect on the vegetative composition beyond a 5–10 m zone immediately adjacent to the pavement.

5.2. Conservation and management implications

Gradient analyses revealed that environmental variables and vegetation were influenced by a strong path-distance gradient. From the path to the inner forest, there was more or less continuous species replacement, suggesting the presence of a gradual ecotone/ecocline, which is characterized by the appearance of particular plant species groups associated to disturbance (e.g. therophytes, transient species, ruderals). Some of those opportunistic plant species may show a trend to spread from path sides into adjacent forest communities, as we could note for *Circaea lutetiana*, *Geum urbanum* and *Urtica dioica*. Furthermore, invasive non-native species like *Impatiens parviflora* and *I. glandulifera* have been found associated with the path environment and could also in the future progressively expand their populations into the forest. This function of corridor or agent of dispersal of introduced species into the interior of managed stands has recently been demonstrated for haul roads in sugar maple forests in Michigan (Buckley et al., 2003). So, even if typical forest species are not completely excluded from the path vicinity, this ecotone is sensitive to invasion of indicators of disturbance. Such sensitivity has obvious implications for both conservation and management. As we already mentioned in a previous study (Godefroid and Koedam, 2003), creating forest paths promotes the so-called "edge effect" within the forest, i.e. the creation of internal edges in the forest. Edge effect makes the functional interior area of a forest smaller than its actual area (Fraver, 1994), and width of the edge zone is critical to the existence of interior habitats in forest fragments (Matlack, 1993). With an edge effect of 3–10 m from both sides of every forest path, our results show that a substantial part of the forest (2.5–8.5%) suffers from banalization due to the presence of these paths. Creating these internal edges in the forest should therefore be avoided, because it will likely enhance the spread of these opportunistic species and might be a threat for conserving woodland flora. Our data at present are insufficient to evaluate if these species will progressively continue to invade the area as far as the core of the forest and entering there in competition with the woodland vegetation, but as precaution we cannot wait until it happens. It could be argued that shade and competition with overstory trees for soil moisture would limit the invasion of adjacent forest by some of these species, but some results tend to indicate the opposite as, in our study area, the inner forest is not more shaded than nearby the paths. As land use intensity increases and the density of human populations grows in areas adjacent to forested land, greater use of the forest is expected. That means growing opportunities for a considerable number of ruderal, if not alien, species. Forest managers should be sufficiently aware of the possible extension of those particularly competitive species. Actually, this problem requires attention and efforts should be made for limiting the use of the most detrimental surfacing materials (e.g. asphalt and dolomite) to the forest in order to minimise the chances of development and spread of these undesirable species representing a possible threat for the optimal development of the typical forest vegetation. If we want to conserve the ecological processes of forests, woodland specialists should be given priority over species which have a greater range of potential habitats, and which are more tolerant of stressful, open environments.

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