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The impacts of road and walking trails upon adjacent vegetation: Effects of road building materials on species composition in a nutrient poor environment☆

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ABSTRACT

Roads represent an important landscape element affecting both biotic and abiotic components. Alteration of soil properties along roads (addition of nutrients) is assumed to have a great impact on vegetation structure especially in nutrient poor ecosystems. Existing studies focus mainly on road dust. In our study we assessed the overall effects of roads upon adjacent alpine tundra vegetation and soils in Krkonoše Mts, Czech Republic. Our aims were to (1) reconstruct the road-related changes using aerial data and GPS mapping to study colonization of roadside plant species; (2) assess the road effects on physical–chemical soil properties and vegetation composition along transects; and (3) propose conservation measures to stop further damage. Changes were reconstructed from historical multispectral aerial photography (1986 to 1997), measured by GPS device (1997, 2004), and accompanied by detailed soil (1998, 2000 and 2001) and vegetation (2000 and 2004) surveys along transects. Along alkaline roads, fast and profound shifts in physical–chemical soil properties (pH increased from 3.9 up to 7.6, base saturation from 9–30% up to 100%), and species composition were recorded. The roadside vegetation doubled in area during the studied decade. Stress-tolerant tundra species were replaced by meso- to nitrophilous species and species preferring man-made habitats. The intensity of changes depended significantly on the type of road material and the position relative to the road (slope position, distance from the road). Our findings support the assumption that alkaline gravel is the main cause of changes along roads in the area, and indicate the leading role of water transport in the soil and consequent vegetation alteration. To prevent the further damage we recommended replacement of alkaline gravel by granite, even though expensive and technically complicated. Based on our recommendations, the National Park authorities started to reconstruct the trails, although recovery is expected to be slow.

1. Introduction

Roads and paths represent important landscape elements having large impacts on the surroundings. They affect both the biotic and the abiotic components of landscape by changing the dynamics of populations of plants and animals, altering flows of material, introducing exotic species, and changing levels of available resources, such as light, water and nutrients (Angold, 1997; Coffin, 2007; Hill and Pickering, 2006; Spellerberg, 1998). The extent and intensity of the effects vary with the position of the road relative to pattern of slope, prevailing winds and surrounding land cover (Forman and Alexander, 1998). The road-effect zone is highly asymmetrical, due to nature's directional flows and the spatial patterns on opposite sides of a road, and has convoluted boundaries (Forman and Deblinger, 2000).

Disruption of the chemical environment (alteration of chemical soil properties) along roads affects plant growth and species diversity and composition (Cape et al., 2004; Spellerberg, 1998; Trombulak and Frissell, 2000; Forman and Alexander, 1998). Many studies on roadsides indicate strong relationship between the spread of non-native plant species and soil nutrient levels (Cale and Hobbs, 1991; Forman, 2000; Johnston and Johnston, 2004). While considerable research has been carried out on the influence of deicing salt (Green et al., 2008; Bryson and Barker, 2002; Cunningham et al., 2008), and pollutants from vehicle exhausts (Angold, 1997; Cape et al., 2004; Djingova et al., 2003; Hooda et al., 2007; Truscott et al., 2005) and brake linings (Grantz et al., 2003; Thorpe and Harrison, 2008; Ward, 1990), the effects of road construction material have been little investigated. The impact is especially profound if alkaline gravel is used in predominantly nutrient-poor environments dominated by stress tolerant plants (Hill and Pickering, 2006). Liming in general significantly increases the soil pH, enhances the rate of decomposition

Abbreviations: (KRNAP), Krkonoše Mts National Park; (GPS), Global Positioning System; (AB), amygdaloidal basaltic rock; (D-AB), mixture of dolomite and amygdaloidal basaltic rock.

☆ Nomenclature source: IUCN categories of threatened species — according to Holub and Procházka (2000).

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of organic matter, provides the basic nutrient cations (Ca and Mg), increases the solubility of Mo and P (Bolan et al., 2003) and increases the amount of NO_3^- in the soil (Bertrand et al., 2007; Schimel et al., 1996). Such processes facilitate colonization by more competitive, often non-native species with greater nutrient uptake efficiency and higher biomass, such as weeds (Dulière et al., 1999; Hobbs and Huenneke, 1992; Chapin, 1987).

Studies on alkalinization effects of roads on the vegetation of acidic soils are relatively few. In Belgium it is reported that a limestone paved road in the acid forest environment can create a locally neutral to alkaline soil in the adjacent community (Godefroid and Koedam, 2004). An early example is a Roman limestone road that locally resulted in alkaline soils in a natural acidic podsol community (Detwyler, 1971). In Alaska along the Dalton Highway the calcareous road dust altered the soil chemistry and microbial decomposition, and in some cases elevated the soil pH to a level toxic to tundra acidophilic plants (Myers-Smith et al., 2006; Reynolds and Tenhunen, 1996; Walker and Everett, 1987). These tundra studies deal with one aspect of the alkaline road influence on grassland vegetation — the effect of calcareous road dust deposition. Our scientific concern – to evaluate the influence of different environmental factors, mainly the overall effect of alkaline road material, the road age, seasonality, tourist load, and position relative to the slope and wind on soil properties and plant species composition of acidophilic grasslands – has not yet been much investigated. Our aims were to (1) reconstruct a decade of road-related changes using aerial data and a GPS device to study the trends and rate of colonization of roadside plant species; (2) assess the impact of roads on physical–chemical soil properties and vegetation composition along transects, especially the effect of stabilization with alkaline gravel; and (3) propose conservation measures to stop further damage.

2. Methods

2.1. Study area

The Krkonoše Mts National Park and Biosphere Reserve (Fig. 1) represents the highest mountain range in the Czech Republic. Uppermost areas situated above the timberline are covered by a particular mosaic of tundra types: (a) lichen tundra (on topmost summits), (b) grassy tundra (grasslands and peat bogs on the two summit plateaus, focus of our study), and (c) flowery tundra (leeward slopes on glacial cirques of the Krkonoše Mts). The ecosystem, called "alpine" or "arctic-alpine tundra", displays affinities with both sub-arctic and high-mountain regions (Gordon et al., 2002), and hosts many endemic, glacial relic, and rare species, and unique geomorphologic components (Jeník and Sekyra, 1995; Štursa, 1998; Müllerová, 2004). The alpine tundra covers 47 km^2, i.e. 7.4% out of the whole area of the Krkonoše Mts (32 km^2 in the Czech part and 15 km^2 in the Polish part of the Krkonoše Mts). It is exposed to extreme climatic conditions, such as strong north-western winds, average temperature of 0 to +1 °C, snow cover for more than 180 days, annual precipitation of 1400 mm, and periodical soil regelation and deflation (Soukupová et al., 1995). It is formed from granitoid massif and metamorphic rocks (mostly mica schist and phyllite) covered with rankers (typical, podzol and lithic), podzols (humus podzol), organozems (pH 3.7 to 5.1) and patches of peat and raised bogs (Štursová, 1985).

Vegetation cover of grassy tundra is composed of mosaic of grassland, scrubland, fens and peat bogs. The most typical plant species include *Pinus mugo* Turra, creating large dense krummholz; *Nardus stricta* L., a typical low competitive stress tolerant grass dominant of dense uniform stands; *Molinia caerulea* (L.) Moench and *Calamagrostis villosa* (Chaix) J. F. Gmelin forming communities of tall grasses and

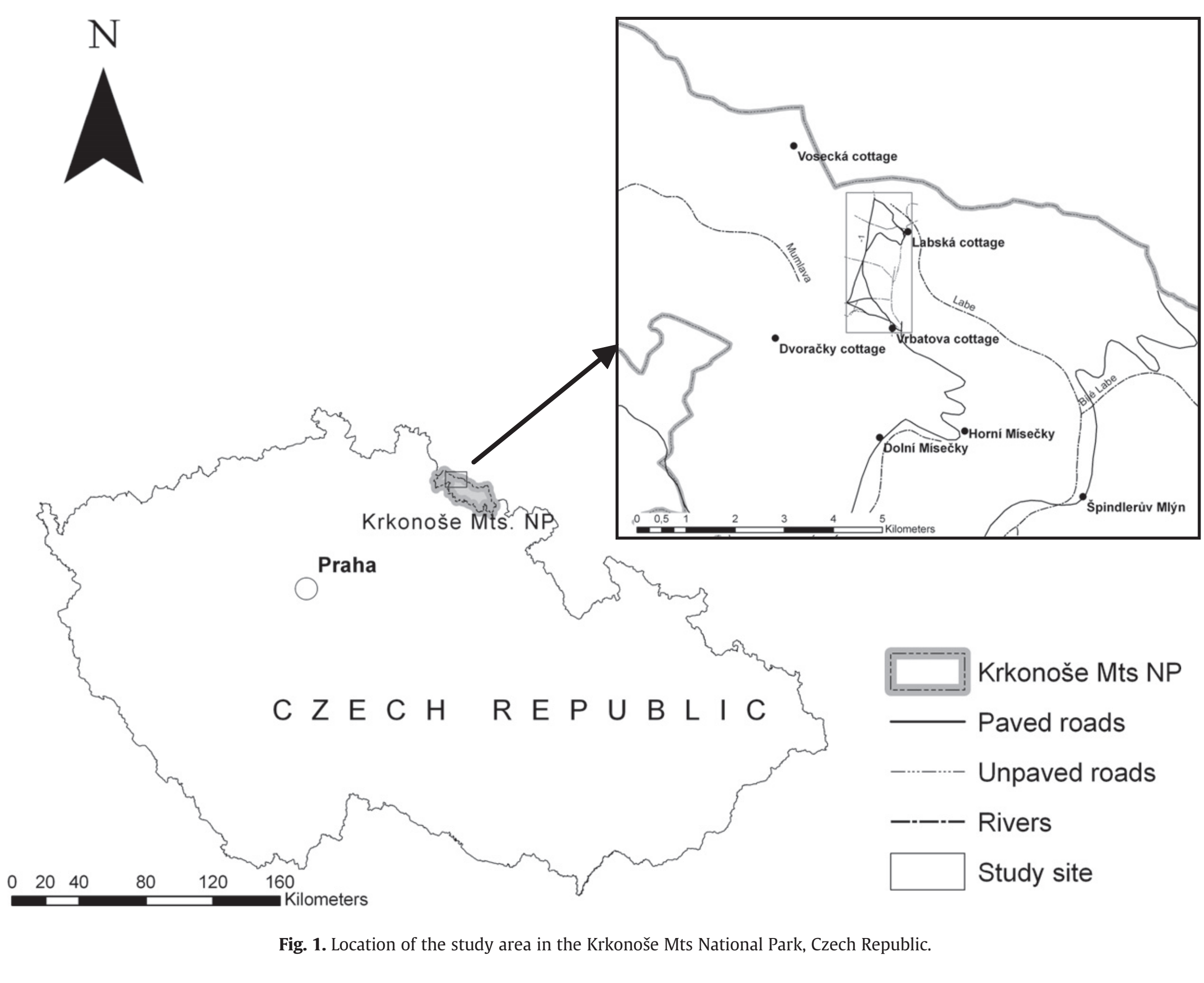

Fig. 1. Location of the study area in the Krkonoše Mts National Park, Czech Republic.

flowering herbs on wet, wind-protected soils; *Deschampsia cespitosa* (L.) P. Beauv., found on mezotrophic to eutrophic deeper, permanently humid soils; peat mosses; and *Trichophorum cespitosum* (L.) Hartm. forming oligotrophic communities of boreoarctic and alpine raised bogs.

Despite the fact that the Krkonoše Mts were declared a National Park in 1963 and a bilateral Biosphere Reserve in 1992, the increasing numbers of visitors (more than eight million per year, with half a million visitors to the tundra zone per year; Gordon et al., 2002) result in trampling, soil erosion, noise, pollution, dispersal of alien plant diaspores, building activities and fragmentation of habitats (Štursa, 1998). Even on the high plateaus, there are numerous chalets, footpaths and roads.

The study site is located in grassy tundra of the western plateau (1300–1350 m a.s.l., 15° 33′ E, 50° 45′ N, app. 1.5 km^2, Fig. 1). It was selected according the available aerial MS photography. Road density in the area is 24 meters per hectare. From the 1970's to 1980's most of paths and roads were stabilized with foreign material – dolomite, amygdaloidal basaltic rock (AB), or dolomite-amygdaloidal basaltic rock mixture (D-AB) – in order to prevent erosion. The only road open for vehicles was stabilized by thick layer of dolomite and AB gravel and covered by asphalt in 1980. Today, extensive strips and lobes of roadside vegetation are present along roads and trails constructed with alkaline material. In the project, six and a half km of roads/walking trails were analyzed, with more than five km of them hardened or paved. The longest were asphalt (2.2 km) and AB roads (1.4 km), dolomite covered 0.8 km and D-AB 0.9 km. The width of stabilized trails was 2 m in average, whereas that of the asphalt road was 3.5 m with 0.3–1 m wide verges of loose gravel. Historical development of trail network was reconstructed from historical and tourist maps (since the end of 16th Century), and from aerial photographs (since 1936). Quantification of traffic intensity was based on data from 1997. During 10 days in the high tourist season the numbers of walking tourists, cyclists and cars were recorded for each hour (9 a.m. till 6 p.m.) in both directions.

2.2. Spatial analyses

Road-related changes were reconstructed using multispectral aerial photographs of 1986 (scale — 1:22000; channels — 0.48, 0.54, 0.66, 0.84 nm), 1989 (scale — 1:22000; channels — 0.54, 0.60, 0.66, 0.84 nm), and 1997 (scale — 1:15000; channels — 0.54, 0.60, 0.66, 0.84 nm), created and provided by the Agency for Nature Conservation and Landscape Protection in Prague. The roadside vegetation could be traced on the multispectral data because it is much taller, has broader leaves and produces a higher biomass than the natural vegetation. The photographs were analyzed digitally — negatives were scanned at 1000 dpi, co-registered by image-to-image registration, and georeferenced using panchromatic orthophotographs (year — 1997; final pixel resolution — 0.5 m; created by Geodézie Krkonoše; provided by the Krkonoše National Park Authority). Second order transformation and the nearest neighbor rectification method were applied at final pixel size 0.5×0.5 m with forty to fifty ground control points. Visuality and separability of roadside vegetation were improved by contrast enhancement (histogram equalization) and principal component analysis (Jensen, 2004). The roadside vegetation was classified using parallelepiped classification (non-parametric supervised method defining the lowest and the highest values of classes in every spectral band; for details see Müllerová, 2004) using software Chips (version 4.3, University of Copenhagen, Copenhagen) and Geomatica (version 10.0, Geomatics Enterprises Inc., Ontario, Canada). Evaluation areas used for the accuracy assessment were randomly positioned (100 samples within roadside vegetation layer, and 100 samples outside the layer but within 50 m of road). User's (the measure of commission error), and producer's accuracy (the measure of omission error) of roadside vegetation class was calculated from the confusion matrix (Congalton, 1991).

Since in 1997 multispectral aerial photographs covered only small part of the study area. To fill the gap in data, a GPS device was used to map the roadside vegetation in 1997/98 and partly in 2004 (due to limited financial sources). The boundaries between roadside and natural vegetation were mapped as areal features with attributes, such as species composition (dominant and abundant species), and position relative to the road (above, below, or in flat terrain). Roads, road edges and cross-drains were mapped as linear features with attributes, such as type of stabilizing material, and width.

A GPS mapping receiver Trimble Pathfinder ProXR was used for measurements with PDOP mask set to 6.0 and elevation mask to 15. The differential correction was processed with base data from a Prague station with the final accuracy of the output data better than one meter. Nonetheless point features representing reference points or single occurrences of species were of higher accuracy due to position averaging. For point measurements minimum of 10 positions was collected in one second frequency. For line and polygon measurements positions were read each 2 s. The RS and GPS data from the overlapping area were statistically tested for the discrepancy. A grid of 5 x 5 pixel squares (number of pixels of roadside vegetation in each square) was used for the analysis instead of direct pixel-to-pixel comparison to eliminate the mis-registration errors and to reduce the large amount of data. Chi-square goodness of fit and regression analysis were performed on the data (Zar, 2010).

The extent of roadside vegetation was spatially examined between years to determine vegetation changes and trends in a GIS environment using ArcInfo (Environmental Research Institute, Redlands). Relations among the extent of roadside vegetation and several factors were tested by variance analysis methods (one-way analysis of variance, ANOVA), and by linear regression (STATISTICA 6 software). The tested variables included: (1) road characteristics, such as type of stabilizing material, construction period, road width, seasonality (accessible all year/summer/winter/closed), traffic intensity (average daily number of walkers/cyclists/cars), and road position to the slope (situated in flat terrain, along or across the slope), and (2) environmental variables, such as vegetation position relative to the road, indicating the effect of runoff water; and prevailing wind direction to or from the road, indicating the wind transport of road particles. Average wind directions were obtained from meteorological station (Czech Hydrometeorological Institute), automatic meteostation (KRNAP), and the study of tree flag forms (KRNAP).

2.3. Vegetation and soil samples along transects

Seven permanent transects were selected randomly at sites of corresponding bedrock and similar terrain morphology to analyze the effects of different road/trail construction material, such as: i) asphalt (transects A1 of 40 m, and A2 of 181 m), ii) AB (transect AB of 46 m), iii) dolomite (transects D1 of 32 m, and D2 of 34 m), iv) D-AB (transect D-AB of 14 m) and v) granite (transect N of 7 m). Transects followed the slope and were perpendicular to a road/trail, with the start and end in undisturbed natural vegetation. Transects were evaluated as a complex comprising of both affected and natural parts, with both ends of transect reaching the natural vegetation considered as controls, comparable to natural stands. A higher number of transects was not possible due to the small extent of vulnerable alpine tundra ecosystem and high risk of ecesis of roadside plant species at sites disturbed by soil sampling.

Vegetation was studied on seventy 1×1 m permanent plots. Vascular plant species, bryophytes and lichens were recorded using Braun–Blanquet's nine-grade semi-quantitative scale of abundance and dominance (Braun-Blanquet, 1964) in 2000, and repeated in 2004 with supplementary information on elevation, slope, aspect, and soil type. Relevés were loaded into TURBO(VEG) 9.39 database (Hennekens and Schaminée, 2001). Permanent plots were distributed along seven transects in the following scheme: the first was positioned above the road in natural vegetation, the others were placed below the road at a two meter and five meter distance, and then every 5 m up to natural vegetation not affected by the road. The interval between plots was enlarged to 10 m starting from the distance of 60 m below the road.

Cover values of species were modified by van den Maarel transformation (Jongman et al., 1995) prior to gradient analysis in Canoco for Windows 4.0 (ter Braak and Šmilauer, 2002). Ordination methods based on the model of linear species response to the underlying environmental gradient (PCA, resp. RDA) were used, because a monotonic distribution of the plant species was assumed. The species were separated into roadside or natural vegetation using PCA. The influence of the soil and landscape characteristics on species composition was studied by redundancy analysis with forward selection (RDA; Jongman et al., 1995). Monte Carlo permutation test (Jongman et al., 1995) with 499 permutations (blocks defined by covariables — codes of transects) was chosen to determine the effect of each environmental variable on 52 relevés and 79 species.

Soil was sampled at the end of the vegetation season (second half of September of 1998, 2000 and 2001) at a total number of 52 sampling points — 23 for asphalt, 10 for AB, 13 for dolomite, 3 for D-AB and 3 for granite. The first and the last sampling points represented controls. Sampling points were positioned on transects at the same scheme as the vegetation permanent plots. At the A1 transect (180 meters long), starting from the forty meter distance below the asphalt road the soil samples for analyzing selected parameters (pH, actual moisture, dry matter) were taken every ten meters, samples for the complete analysis every thirty meters. The D-AB transect differed significantly from others, as it was situated: 1) on a trail closed to the public at the end of the 1970's, whereas other trails are still in use; and 2) in flat terrain, whereas the other transects were situated on slopes. Its' verges were therefore much narrower with only three sampling points.

Soil samples were gathered with a soil probe next to the permanent plot. Part of the sample used for examining actual moisture, dry matter, pH, content of nitrates, and exchangeable phosphorus, was immediately sifted through a 2 mm sieve and transported to the laboratory in airtight 100 ml bottles placed in cooler. The fine earth of the sample was dried at room temperature for other analyses. The soil skeleton was calculated as a ratio of inorganic particles up to 2 mm and fine earth. Values of active pH were measured according to McLean (1982). Methods of Moore and Chapman (1986) were used to determine base saturation by exchangeable cations (Ca^{2+}, Mg^{2+}, K^{+}, H^{+}, Al^{3+}) and the content of nitrates. Exchangeable phosphorus was measured by the photometric method following Olsen (1982). Total carbon and nitrogen content were analyzed according to Monar (1972). Carbonate concentration was determined by ISO/DIS 10693 (1995). Potential direct solar irradiation (PDSI) was calculated for each plot from data on exposition, slope and angular height of the horizon at these cardinal points following Jeník and Rejmánek (1969). To identify the most important environmental gradients, principal components analysis (PCA; Jongman et al., 1995) was used to detect correlations among site attributes (slope, PDSI), road distance, type of paving material, physical-chemical soil properties (soil skeleton, dry matter, pH, Ca^{2+}, Mg^{2+}, K^{+}, Al^{3+}, H^{+}, base saturation, N-NO_3^-/N, carbonates, N, C, and P_{ex}), and vegetation characteristics (vegetation cover, total number of plant species, number of roadside plant species, and natural composition represented by rate of autochthonous species in relevé). Since the number of environmental characteristics was relatively high (29) compared to the number of soil sampling points (52), the environmental characteristics were used as species data in Canoco (scaling and standardizing were needed because of different units).

3. Results

3.1. Reconstruction of road-related changes using aerial data and GPS mapping

The area of roadside vegetation grew considerably from 2% of the study area in 1986 (2.5% considering the grassland area only — i.e. excluding Dwarf Pine stands) up to 6.2% (7.6% of grasslands) in 1997 (Fig. 2). The measured rate of spread (1986/1997) was 0.6 hectare per year, with an increase of 0.28 times per year. Based on the measured increase (0.25 times per year in 1997/2004), roadside vegetation was estimated to cover 7.7% (9.4% of grasslands) in 2004 (Fig. 2). Between-year-changes at the pixel level (0.25 m^2) were analyzed using the 1986 and 1989 multispectral aerial photographs and 1997 GPS data. Four different responses of the roadside vegetation were recorded — increase (6.3% of the area), decrease (2.5%), stable (i.e. remained constant; 0.6%) and irregular (3.5%). The results showed a significant increase in roadside vegetation in time. Changes in vegetation along hardened roads were significantly greater (up to 4.7 times in 1997) than along unhardened; with the asphalt road (built of several layers of dolomite and AB gravel) having the greatest change (Fig. 2).

Of the total 6.5 km of roads, 3.1 km were bordered by roadside vegetation in 1986, 3.5 km in 1989, and 5.1 km in 1997. In 1997 asphalt, dolomite and D-AB roads were nearly all bordered with roadside vegetation. The most rapid increase during the decade was recorded along AB (2.7 times) and asphalt roads (2.1 times). D-AB and unhardened trails were relatively stable, with more than 90% of the first and less than 20% of the second bordered with roadside vegetation over the whole period.

The area of roadside vegetation in the vicinity (within 50 m) of the asphalt road enlarged almost five times over a period of ten years, covering 25.5% of the road vicinity in 1997. Along other types of road it increased from 1.5 times (dolomite covering 11.5%, D-AB 9.7%) to 2.7 times (AB 7.2%). Along unhardened walking trails it covered maximally 4%.

From the environmental factors tested, the extent of roadside vegetation was significantly related to the road stabilizing material ($p<0.001$), and position relative to the road ($p=0.0087$; Fig. 3). Position to the wind, road frequency, seasonality, and construction period did not show significant relationships. The role of road width and the type of traffic could not be statistically determined, as they were closely interrelated to the type of stabilization material (as the asphalt road was much wider compared to others, and it was the only road used by vehicles).

Results of 1986 and 1989 could not be ground-truthed, so the classification accuracy was evaluated by visual photo interpretation of stratified random samples. The accuracy of the roadside vegetation class in 1986 was 78% (user's), and 92% (producer's accuracy). In 1989 it was 79% (user's), and 87% (producer's accuracy). The overall accuracy was 85.5% in 1986, and 83.5% in 1989. The interpretation of 1989 aerial photographs was also compared with the field map of Fišerová (1991; see Müllerová, 2004). In this case the accuracy reached 73% (user's), and 75.3% (producer's accuracy). However this map focused on natural communities and the roadside vegetation was of marginal interest, and the accuracy therefore reached lower values. In 1997 aerial data were only available for a small part of the study area. Field measurements of roadside vegetation using the GPS device were accomplished, and the two methods (multispectral photography analyses and field GPS measurements) statistically assessed using the data for the overlapping area. The chi-square goodness of fit showed significant differences at $\alpha=0.05$ but not at $\alpha=0.01$ ($\chi^2=6.41$, df$=1$, $0.01<P<0.05$), so the two methods may be comparable with some limitations.

3.2. The road impact assessment along transects

Based on the PCA, the species recorded on transects were separated into two groups (online supplement). Relevés of natural plant communities were placed at right side of the ordination diagram in Fig. 4, roadside vegetation at left side. The roadside vegetation included: a) species preferring man-made habitats (synanthropic), b) species of lower altitudes, and c) competitive local species favored by the new conditions, which naturally grow in patches of humid tundra richer in

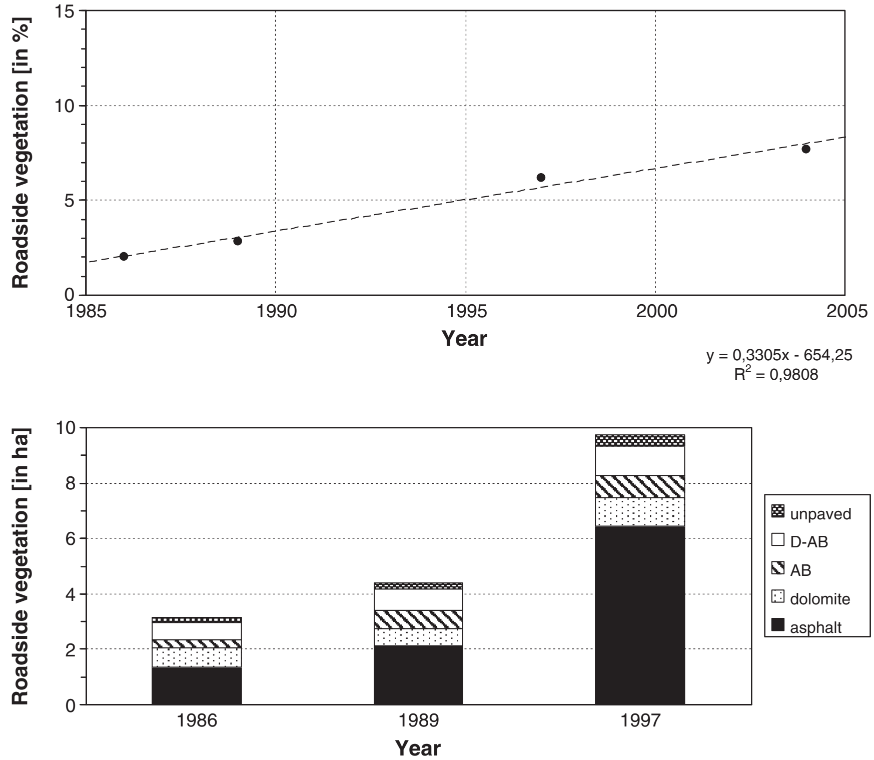

Fig. 2. Dynamics of roadside vegetation changes in percent (measured overall extent with future prospect); and in hectares (divided by the type of road pavement as the main factor explaining the vegetation changes; D-AB – mixture of dolomite and amygdaloidal basaltic rock, AB – amygdaloidal basaltic rock). In 2004, only part of the study area was investigated due to the limited financial sources. Based on the measured increase (1997/2004), the share of roadside vegetation in 2004 was estimated.

nutrients, such as terrain depressions, stream alluviums and stands of *Pinus mugo*, and at sites with long-lasting snow cover (Table 1). In the road vicinity (within 10 m from the road, down the slope), the proportion of roadside species was significantly higher than at distances greater than 20 m, or above the road (up the slope).

Soils covered by natural vegetation showed low values of pH (3.9 to 4.2) and base saturation (9 to 30%) with hydrogen and aluminum playing the main role among exchangeable cations (Figs. 5 and 6). High accumulation of soil organic carbon, nitrogen, and N/P_{ex} ratio can be ascribed to the high ratio of poorly decomposable biomass of grasses in O_h soil horizon of autochthonous communities. Physical–chemical soil conditions along roads were significantly different from natural stage (Figs. 5 and 6). Near the road the active pH reached up to 7.6 with base saturation 100%, representing slightly alkaline, eubasic and highly saturated soils, found nowhere else in the study area. PCA ordination (Fig. 6) showed that compared to the natural conditions, the soils were drier with more skeleton. Ca^{2+} and Mg^{2+} played the main role in adsorbing complex. Organic biomass mineralization ran faster, $N\text{-}NO_3^-/N$ ratio reached higher values, and contents of total carbon and nitrogen were much lower.

Chemical soil characteristics (pH and base saturation) depended strongly on sample position relative to the road (Fig. 5). Samples situated above the built roads (up the slope) reached values corresponding to natural stands while below such roads (down the slope) the values were

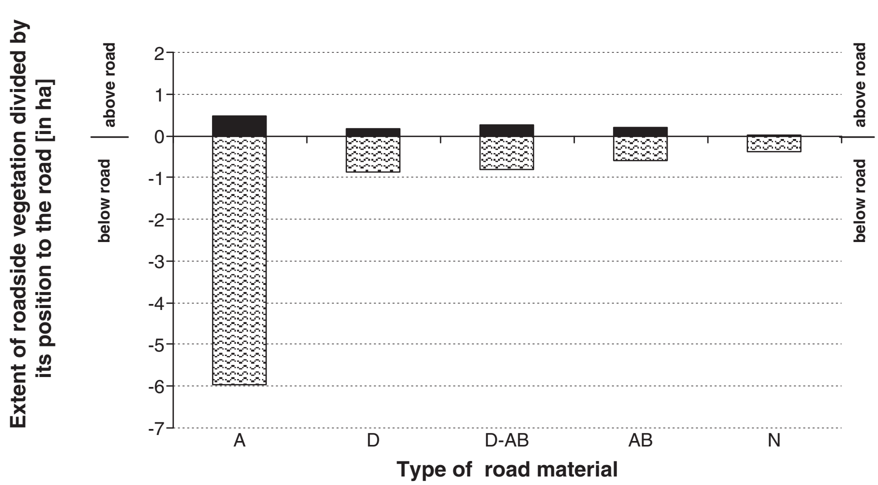

Fig. 3. Extent of roadside vegetation along differently stabilized roads in 1997 divided by its position relative to the road (above or below; A — asphalt; D — dolomite; AB — amygdaloidal basaltic rock; D-AB — dolomite-amygdaloidal basaltic rock mixture; N — granite).

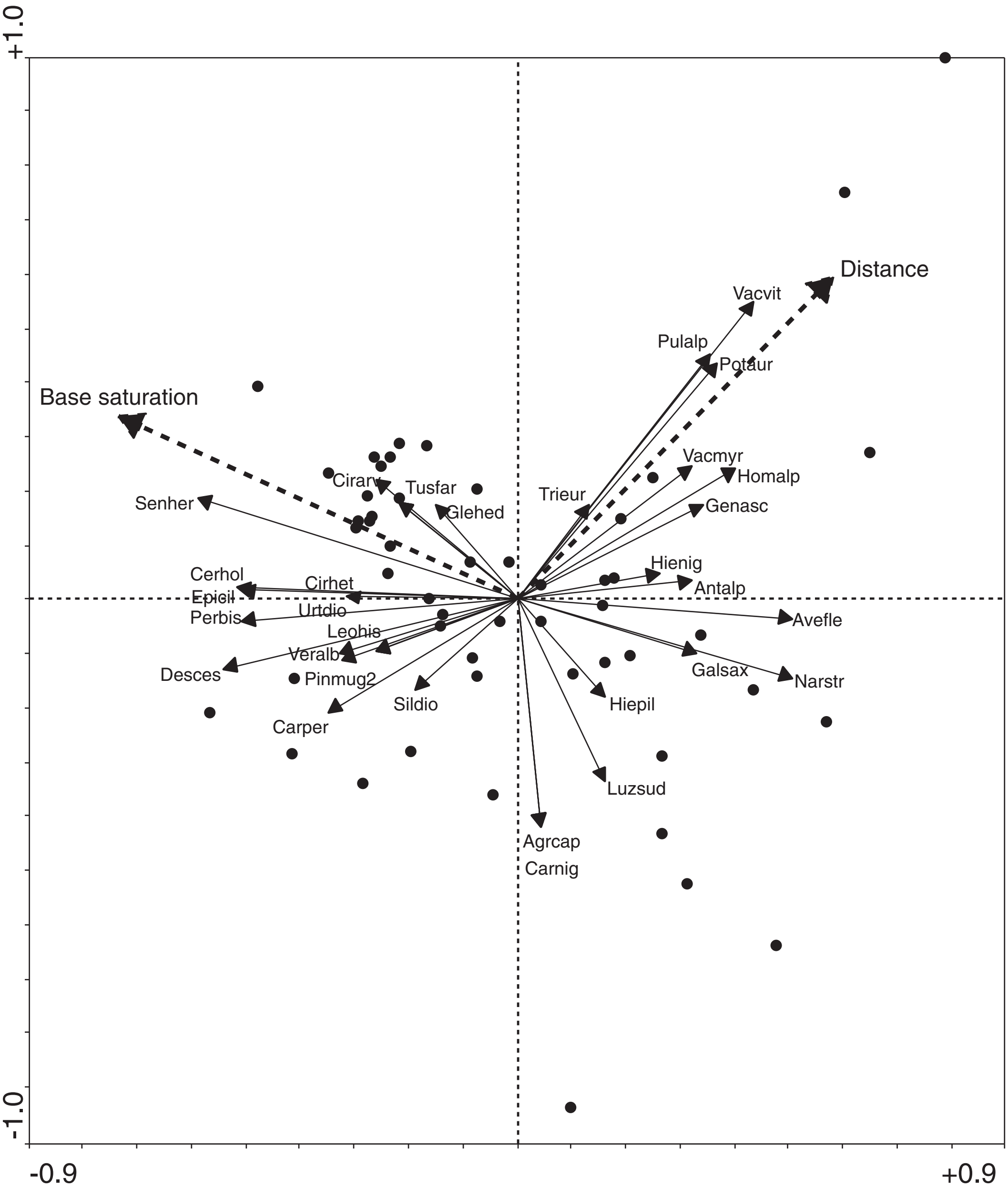

Fig. 4. RDA ordination diagram of 52 relevés from seven transects across differently paved roads arranged according to the linear response of 79 species (arrows). Dashed arrows indicate the most important environmental variables explaining the changes in vegetation along roads — base saturation in soil horizon A and distance from the road. Plant abbreviations include the first three letters of both the genus and species names given in online supplement; only species with fit ≥ 10% are shown. Relevés were separated into road-altered (left side of the diagram) and natural vegetation (right side). The two canonic axes explain 22.3% of the variability in the dataset. Monte-Carlo permutation tests of the first canonical axis and of all canonical axes were significant.

comparably augmented. Dolomite and asphalt had the strongest effects, with maximum values of active pH 7.4 and 7.6, respectively, and base saturation up to 100% (Fig. 5). Mg^{2+} and Ca^{2+} in the adsorption complex along dolomite and asphalt roads reached much higher values compared to natural stands, with a positive content of carbonates detected. Along dolomite trail, the maximum values of pH(H_2O) and base saturation were recorded right below the trail (within 1–2 m), while below the asphalt road the peak occurred at a distance of 9.5 m. Along AB trail soil physical–chemical conditions were similar to the natural conditions. Although an increased Ca^{2+} content of the adsorption complex was detected below such trail, Al^{3+} was still the dominating exchangeable cation at all distances, just as in natural stands.

The most important environmental variables associated with the changes in vegetation along roads, indicated by RDA, were base saturation in soil A horizon ($p = 0.002$) and distance from the road ($p = 0.002$, Fig. 4). These two variables explained 22.3% of the overall variability in the data; base saturation itself explained 16.5%, road distance 11%. The next environmental variables with the large influence such as pH, concentrations of Ca^{2+}, Al^{3+}, total carbon and nitrogen were narrowly correlated with the base saturation and they were not statistically significant after adding this variable into the analysis. Other physical–chemical soil properties and landscape elements had only low and non-significant influence.

Changes in vegetation structure affect comparably large areas of the alpine tundra ecosystem, unique to Central Europe, hosting many species of high conservation (some endemic). While meso- to nitrophilous species of tall grasses and robust herbs spread along the roads, many local stress-tolerant low competitive tundra species either disappear, or survive only in a sterile form. This applies also to the rare and protected species (Table 1). Sixteen IUCN threatened

Table 1
Responses of vascular plants to the road disturbance with examples of typical species. Endangerment by IUCN Red list criteria is marked in brackets (CR — critically endangered, EN — endangered, VU — vulnerable, NT — near threatened).

Responses to the road disturbance	Type	Species
Favored species	Species of man made habitats (synanthropic)	*Cirsium arvense* *Epilobium angustifolium* *Epilobium ciliatum* * *Plantago major* *Ranunculus repens* *Rumex alpinus* * *Taraxacum* sect. *ruderalia* *Urtica dioica*
	Species of lower elevation	*Achillea millefolium* *Hypericum perforatum* *Lotus corniculatus* *Poa compressa* *Prunella vulgaris* *Senecio ovatus* *Thlaspi perfoliatum*
	Competitive local species favored by the new conditions	*Calamagrostis villosa* *Campanula bohemica* (EN, endemic) *Cirsium heterophyllum* *Deschampsia caespitosa* *Persicaria bistorta* *Senecio hercynicus* *Veratrum album* subsp. *lobelianum* (NT)
	Rare species preferring open stands	*Malaxis monophyllos* (CR)
	Rare species preferring alkaline soils	*Botrychium lunaria* (EN) *Gentianopsis ciliata* (VU)
Disappearing species	Local stress-tolerant low competitive species	*Anemone narcissiflora* (CR) *Calluna vulgaris* *Gentiana asclepiadea* (NT) *Hieracium nigrescens* (EN, endemic) *Hieracium alpinum* (VU) *Homogyne alpina* ** *Hypochaeris uniflora* ** (VU) *Nardus stricta* *Potentilla aurea* (NT) *Pulsatilla alpina* subsp. *austriaca* (VU)

* Non-indigenous.
** Only sterile plants survive.

species have disappeared along roads in the area. Only during 2001–2004 period, four protected species reduced their cover or disappeared on transects itself (mostly from 30 to 120 m below the asphalt road).

4. Discussion

Our results showed fast changes in soil properties and species composition along roads in the study area. The expansion of roadside vegetation reflects improved nutrient availability resulting from the increase in pH (Fig. 7). In ecosystems with predominantly nutrient-poor soils dominated by stress tolerant plants, addition and augmented release of nutrients constitute a major disturbance, which has been shown in many examples to facilitate colonization by more competitive, often non-native species (Cale and Hobbs, 1991; Hobbs and Huenneke, 1992). Recorded augmentation of soil pH and base saturation agrees with findings of Wagnerová (1995) from the same study area (next to the road the pH reached 6.2 to 7.3) and Auerbach et al. (1997) from arctic tundra (regular pH 4, next to the road pH augmented up to 7.3).

Close to the road we found a high cover of synanthropic species and robust herbaceous plants, with higher number of vascular plant species and lower cover of mosses (Fig. 6, Table 1). With increasing distances from the road the vegetation became dominated by less competitive stress-tolerant species such as *Nardus stricta* L. This shift in species composition reflects nutrient enrichment and disturbance along roads. The border between the natural and roadside vegetation was sometimes wide with unstable transitional vegetation of both categories.

The spread of roadside vegetation followed the slope. On terrain depressions leading down the slope from alkaline stabilized roads the roadside vegetation formed lobes reflecting the nature of the terrain and reaching far into undisturbed vegetation (up to 156 m from the asphalt road). In flat terrain, *Deschampsia caespitosa* L. (P.) Beauv. formed continuous narrow edges on both sides of stabilized trails. Changes in soil properties were also significantly dependent on the position relative to the road. This provides evidence of the role of water erosion in transporting particles leaching from road building material into the surroundings (c.f. Tossavainen and Forssberg, 1999). Dissolved nutrients from the road stabilizing material were transported down the slope and deposited on existing soil and vegetation (c.f. Forman and Alexander, 1998), gradually enriching originally nutrient-poor soils. This process is enhanced by high precipitation in the area. In other tundra studies (such as Auerbach et al., 1997) the road dust deposition was suggested to be the leading driver of road related vegetation changes. However, in our study the role of wind transport of alkaline particles was not found to be significant. On the other hand our results indicated that water transport plays an important role in soil alteration process (Fig. 7), and therefore we believe it deserves more attention in tundra ecosystem studies.

Asphalt road constructed with large amounts of dolomite and AB gravel was found to have the strongest effects on vegetation and soil properties. Compared to others, the peak in pH and base saturation values along asphalt road was shifted to 9.5 meters distance below the road. One of the reasons for such a shift could be the differences in water flow. During heavy rains the water flows fast over impermeable asphalt surface and graveled surfaces benching, and alkaline particles can thus drift further from the road. The slowly weathering AB had significantly less of an effect on soil and vegetation than easily dissolving dolomite. This could be explained by different times of building of the roads (dolomite road in 1970's, AB road in 1980's). Although AB seems to be less harmful than dolomite, its chemical composition with four times less CaO and MgO and 25 times more SiO_2 is still very different from natural bedrock.

While many rare or threatened tundra species disappear from the road surroundings, it can also provide suitable habitat for some rare species preferring nutrient rich, open or alkaline stands (Table 1). Among the local rare species favored by the roadside disturbance are endangered *Campanula bohemica* Hruby (endemite of Krkonoše), and near threatened *Veratrum album subsp. lobelianum* (Bernh.) Arcang. There are also new rare species appearing along alkaline stabilized roads that are present nowhere else in the area and illustrate dimension of road disturbance. Vulnerable *Gentianopsis ciliata* (L.) Ma is basiphilous species preferring xerophilous habitats and occurring rarely in mountain areas. Its natural elevational maximum in the Krkonoše Mts. is 850 m a. s. l. It was probably introduced to the alpine tundra (altitude of 1370 m a. s. l.) with dolomite used for road pavement. Its flourishing population is exclusively tightened to the body of former dolomite trail that was closed to the public thirty years ago and the population is slowly enlarging. Endangered *Botrychium lunaria* (L.) Sw. occurs naturally on meadows, pastures, screes, as well as in light forests, growing on alkalic to slightly acid soils. In the studied area it is found on disturbed stands on road edges with open trampled vegetation without respect to the type of paving material. It usually occurs in fertile solitary individuals, rarely forms more continuous stands. In 2005 three flowering individuals of critically endangered orchid species typical for colder and mountain areas *Malaxis monophyllos* (L.) Sw. were found in the road vicinity (1365 m a. s. l.). This occurrence represents the new elevational maximum of the species in the Czech Republic, and in Krkonoše Mts. the only other occurrence is in similar biotope of lower altitude (1198 m a. s. l.).

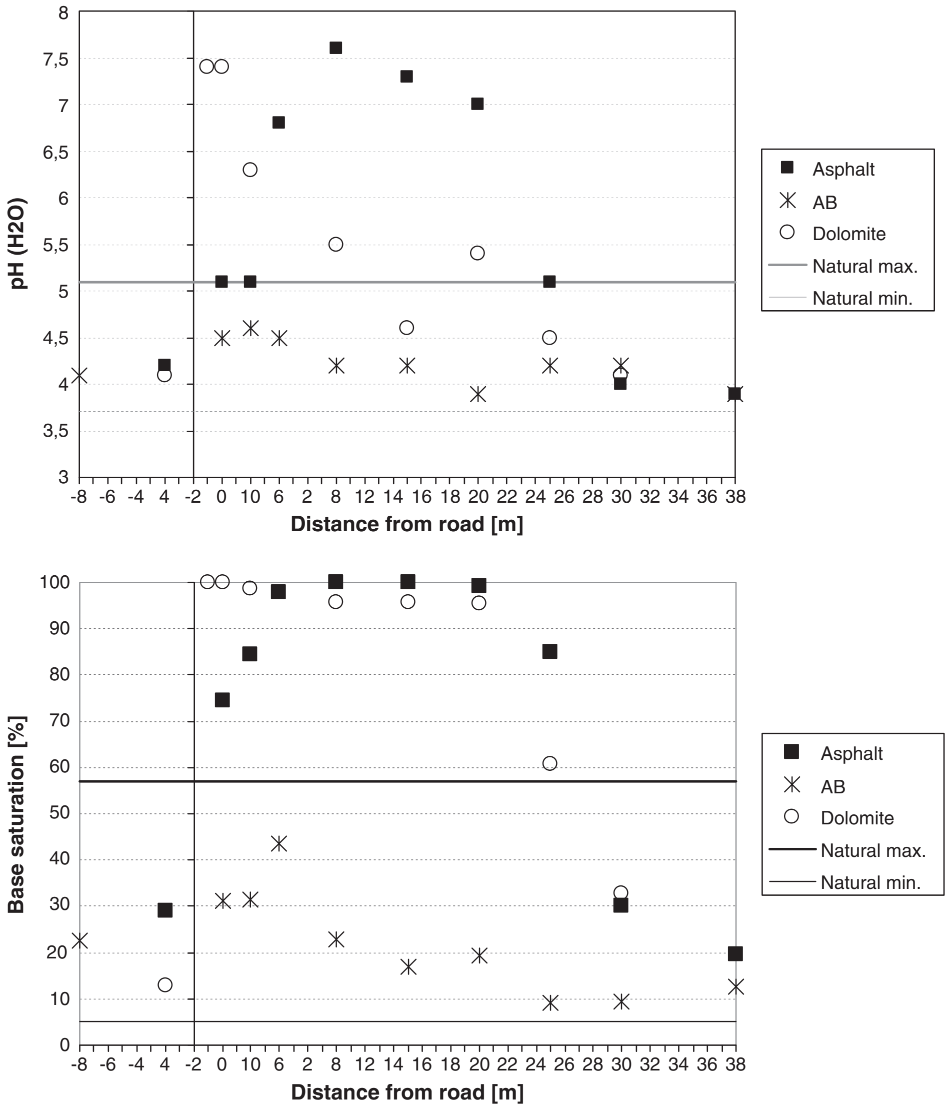

Fig. 5. Relationships among soil pH, base saturation, and the distance from roads stabilized with different material (AB — amygdaloidal basaltic rock). Transects of similar length A2, D1 and M were used in the figure. The orientation of transects followed the slope. Negative values for distance indicate the sample location "above" the road (up the slope); positive values indicate location "below" the road (down the slope, in the direction of flow of particles leaching from the road material). The first and the last samples were located in natural vegetation and represent the controls. The range of natural values (minimum–maximum) indicated by the lines is set according to Štursová (1985).

From such examples we can see profound shifts in species composition in the area. The extent of the road effect and high rate of spread of roadside vegetation indicated that the affected area has grown considerably. Repeated GPS measurements in 2004 confirmed high rate of roadside vegetation increase (0.28 times per year in 1986/1997, 0.25 in 1997/2004). According to these findings the hypothetical constant rate the road-affected area could cover is 13% of the study area by 2020. Expressive changes in vegetation structure of the alpine tundra might happen if no effective conservation measures were applied.

Considering the dimension and rate of changes in vegetation composition and biodiversity losses we proposed replacing the alkaline gravel by granite, especially from the asphalt road, even thought expensive and technically complicated. Instead of macadam pavement we recommend the use of flagstone granite pavement to stabilize the roads suffering from water erosion. Although we consider the removal of alkaline material necessary to stop the alpine tundra ecosystem damage, we are aware that the reconstruction of trails (substitution of alkaline gravel by granite) represents a large interference with the fragile tundra ecosystem. During reconstruction roadsides (ca 2 meters wide) are often disturbed and cleared of vegetation, and such stands become subjected to ecesis of synathropic species.

The ability of alpine tundra to recover in the extreme climatic conditions of Krkonoše summit plateau is limited and the process is expected to be slow. Estimates of the time required for recovery of severely degraded tundra range from more than 15 years (Scherrer and Pickering, 2006) to more than a century (Willard et al., 2007), or the recovery may not happen at all (Harper and Kershaw, 1996; Strandberg, 1997). Still, regarding the comparably fast recovery of disturbed sites in the study area (bodies and surrounding of the two former roads closed thirty years ago), although not so severely damaged, we consider the restoration possible. Based on our recommendations, the National Park Authorities started to reconstruct the trails in 2005.

5. Conclusions

The results of this study revealed that the changes in tundra ecosystem can be fast. The study recorded expansion of roadside and local competitive species deep into the natural vegetation (doubled in size during the studied decade), which resulted in the displacement of local plant communities and suppression of valuable and threatened species. Our findings support the assumption that the alteration of environment that resulted from the building of alkaline roads in the

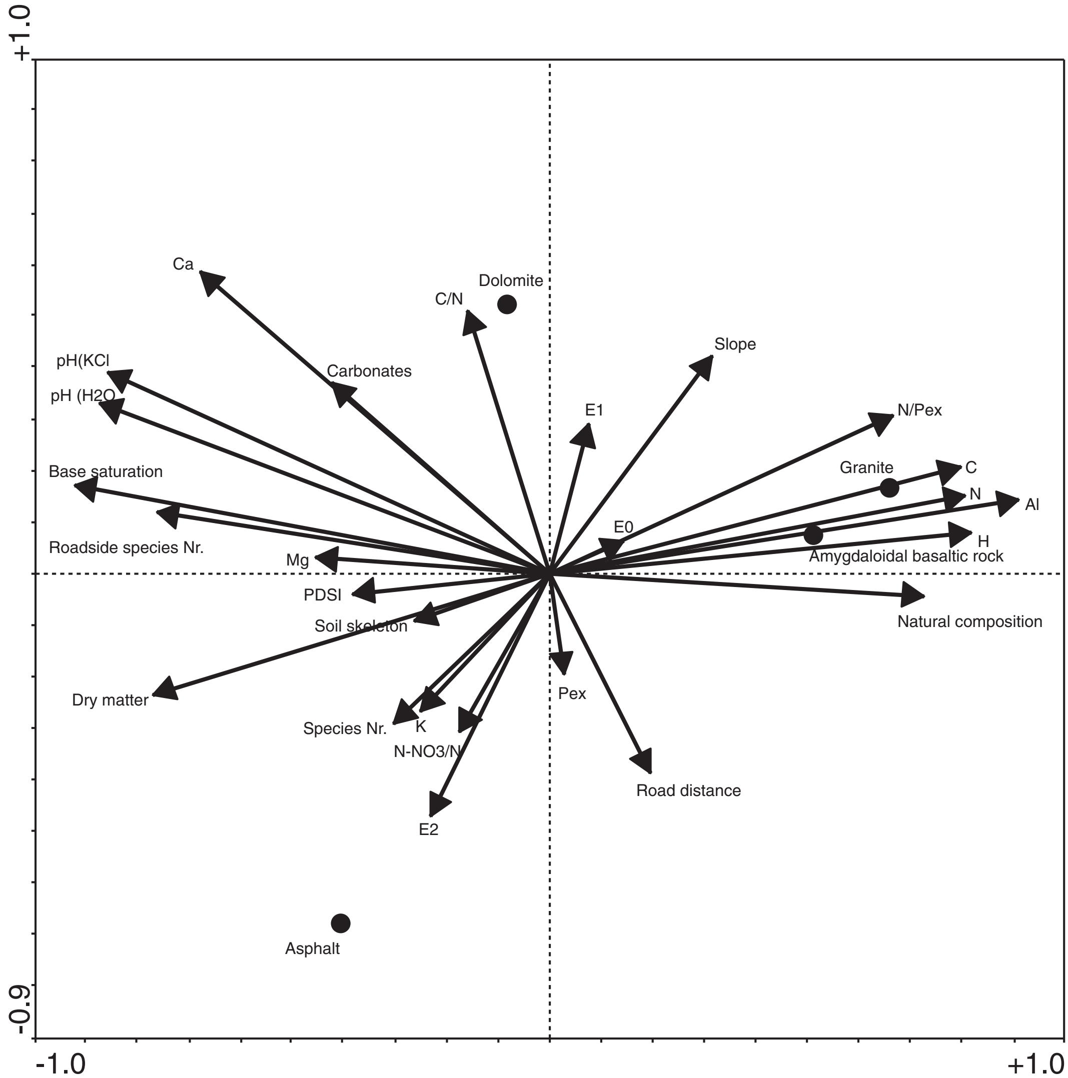

Fig. 6. Correlations among soil, landscape characteristics and species composition. PCA ordination diagram of 52 relevés from seven transects across differently paved roads. Points display categorical variable as the type of paving material (granite, amygdaloidal basaltic rock, dolomite, asphalt). Arrows represent quantitative variables as the site attributes (slope, PDSI), road distance, physical–chemical soil properties (soil skeleton, dry matter, pH, Ca^{2+}, Mg^{2+}, K^{+}, Al^{3+}, H^{+}, base saturation, N-NO_3^-/N, carbonates, N, C, and P_{ex}), and vegetation characteristics, such as cover of the shrub (E_2), herb (E_1), and moss layer (E_0, no lichens were present); total number of plant species; number of roadside plant species; and natural composition (scores of plant species on first PCA axis expressing rate of autochthonous species in plot; see online supplement). These variables (29) were used as species data, scaling, and standardizing were performed due to usage of different units. The first axis explains 31.2% of the variability in the dataset.Correlations among soil, landscape characteristics and species composition. PCA ordination diagram of 52 relevés from seven transects across differently paved roads. Points display categorical variable as the type of paving material (granite, amygdaloidal basaltic rock, dolomite, asphalt). Arrows represent quantitative variables as the site attributes (slope, PDSI), road distance, physical–chemical soil properties (soil skeleton, dry matter, pH, Ca^{2+}, Mg^{2+}, K^{+}, Al^{3+}, H^{+}, base saturation, N-NO_3^-/N, carbonates, N, C, and P_{ex}), and vegetation characteristics, such as cover of the shrub (E_2), herb (E_1), and moss layer (E_0, no lichens were present); total number of plant species; number of roadside plant species; and natural composition (scores of plant species on first PCA axis expressing rate of autochthonous species in plot; see online supplement). These variables (29) were used as species data, scaling, and standardizing were performed due to usage of different units. The first axis explains 31.2% of the variability in the dataset.

1970's to 1990's represents a major driving force of changes The expansion of roadside vegetation reflects improved nutrient availability resulting from the shifts of physical–chemical soil properties along roads stabilized with alkaline material with water transport playing the crucial role.

Arctic-alpine tundra represents a unique ecosystem in Central Europe of high conservation value hosting many rare and protected species including endemites. Long-term monitoring and detailed research of abiotic and biotic processes is important for its correct and effective management. Because future climate warming is expected to increase soil nutrient availability in tundra (Hobbie et al., 2002) similarly to the described road effect, the response of this sensitive ecosystem to climate warming could be similar to the vegetation changes described by our research (yet without supply of synanthropic species such as in our case). Ongoing successive changes along roads of arctic-alpine tundra environment and vegetation recovery along reconstructed trails will be monitored in further research.

Supplementary materials related to this article can be foundonline at doi:10.1016/j.scitotenv.2011.06.056.

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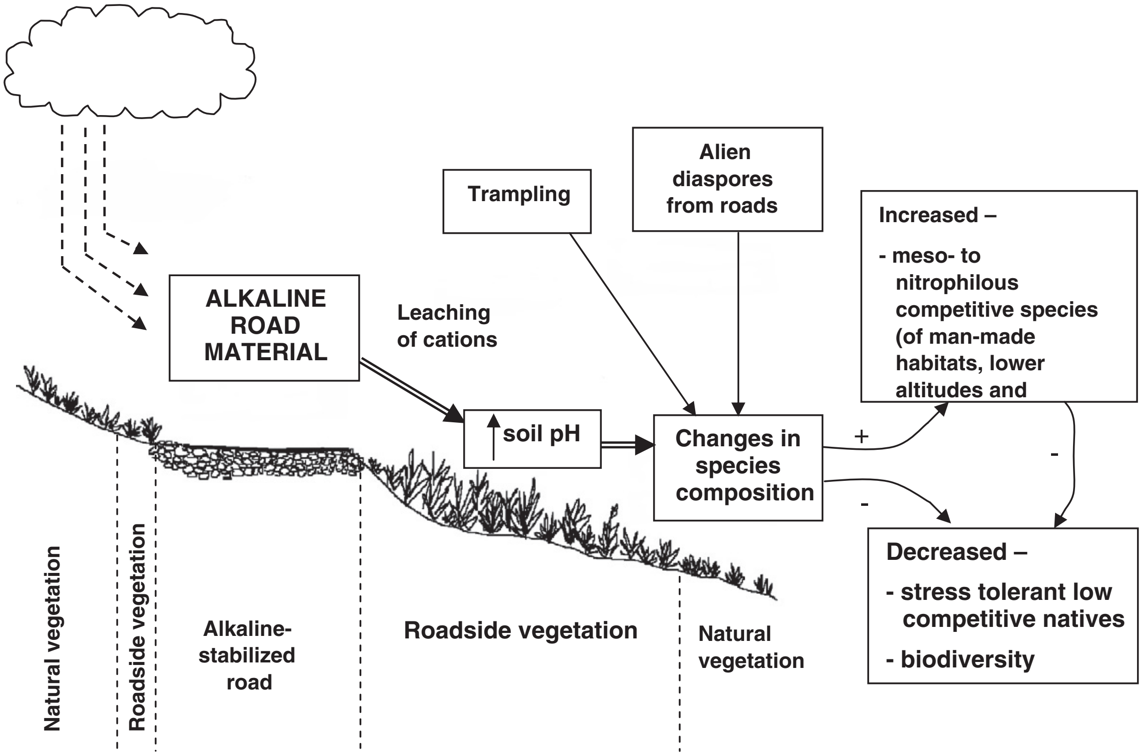

Fig. 7. Conceptual model of driving forces of studied changes in vegetation and soil conditions along alkaline roads.

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