



# The impact of road disturbance on vegetation and soil properties in a beech stand, Hyrcanian forest

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## Abstract

The ‘road-effect zone’ is a concept developed to describe the impact of road construction on the surrounding area. Although many aspects of the road-effect zone have been investigated, the road-effect zone on soil properties (pH, bulk density, soil moisture, electrical conductivity, organic matter (%), C (%), total N (%), available Na, Ca, Mg, P, and K), light regimes (leaf area index and canopy cover), and a Raunkiaer’s life-form classification of plants remains poorly understood, especially in oriental beech (*Fagus orientalis* Lipsky) forests. Hence, the main aims of this research were to estimate the extent of the road-effect zone and to identify the main environmental changes due to forest roads. Specifically, we aimed to evaluate road-effects on: (1) the composition of herbaceous species and tree regeneration (up to 100 m distance from the forest road); (2) the light regime; and (3) soil properties, potentially related to changes in ecosystem functions and composition. We observed that forest roads can have significant impacts on soil, stand characteristics, and vegetation composition. The estimated road-effect zone extended up to 30 m from the road edge. Landscape planners should be aware that road-effect zones can potentially influence the ecology and environmental conditions of an area up to 30 m from the road edge.

**Keywords** Canopy cover · *Fagus orientalis* · Iran · Leaf area index · Road-effect zone

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## Introduction

An extensive and expanding road network enables us to reach previously remote parts of the world and gives us access to vital resources. Global road networks have been expanding at a rapid rate since the 1900s (Forman et al. 2003), such that roads are now a distinctive feature in any landscape, with many countries giving 1–2% of their land surface over to roads and roadsides (Forman and Alexander 1998). In many emerging economies (e.g., Iran), road building is vital for stimulating and maintaining economic growth. Roads today cover approximately 3% of land area in Iran and 1% of the area in the Hyrcanian forest (MRUD 2014). Forest roads are constructed in forest ecosystems in order for humans to perform a variety of activities, including timber and wildlife management, recreation, and to manage fire, pests, and pathogens within the forest. Although forest roads are used by fewer vehicles than asphalt roads in urban areas, they still have a negative impact on plant and wildlife biodiversity (e.g., Trombulak and Frissell 2000; Benítez-López et al. 2010; Marcantonio et al. 2013; Deljouei et al. 2014, 2017a). Large financial investments into road building

could provide opportunities to improve the environmental performance of the existing forest road network, as well as to inform forest planning and design using road ecology, in order to avoid unnecessary negative effects of the road.

Roads and their associated vehicular traffic have adverse impacts on the natural environment at multiple spatial scales, from microclimatic processes in the road corridor, to population dynamics and dispersal of species inhabiting the nearby area (Forman and Alexander 1998; Spellerberg 1998; Trombulak and Frissell 2000; Forman et al. 2003). Roads can have severe environmental impacts, such as soil erosion (Grace and Clinton 2007), slope failures, mass movement of soil (Amaranthus et al. 1985), and habitat fragmentation (Flory and Clay 2006). Roads may also contribute to erosion and sedimentation rates at the catchment scale, due to the abundance of exposed soil in the corridor close to the road, and on road surfaces, from which several chemical contaminants and heavy metals are also transported by runoff into stream networks, lakes, wetlands, and ponds (Sriyraj and Shutes 2001; Forman et al. 2003). In addition, road-edge effects include increased desiccation stress, windshear, and wind turbulence, all of which can increase the rates of tree mortality and damage (Laurance et al. 2001; Nepstad et al. 2001). Plants may further be affected by the fact that they are preferentially transported along road corridors due to seed dispersal by birds (Levey et al. 2005), vehicles (Lonsdale and Lane 1994; Bernhardt-Römermann et al. 2006), and as a result of road maintenance activities (Christen and Matlack 2009), as well as multiple combinations of other dispersal modes (Tikka et al. 2001; Lavoie et al. 2007). In general, the magnitude of these road-effects at a given location is conversely associated with distance from the road (Forman and Alexander 1998), but is also positively correlated with road size (Munguía-Rosas and Montiel 2014). For example, as distance to the road decreases, changes in species diversity and abundance (Deljouei et al. 2017a), as well as in hydrological flows (Coe et al. 2004), erosion and sedimentation rates can be observed. Comparing a control position unaffected by the road (100 m far from the road edge), with plots closer to the road edge, allows us to quantify the “road-effect zone.” This approach has become a central methodology in road ecology studies (Forman and Lauren 1998; Forman and Deblinger 2000). The road-effect zone, first proposed by Forman and Alexander (1998), refers to “the distance perpendicular to any point at a road within which environmental changes can be significantly distinguished from a control location.”

The Hyrcanian forest (Caspian forest) is a green belt which extends over the northern slopes of the Alborz mountain ranges, and covers the southern coasts of the Caspian Sea in Iran. This forest covers land situated at altitudes from 0 to 2800 m above sea level (a.s.l.) and includes multiple forest types composed of 80 woody species of vegetation

(trees and shrubs). Due to a humid temperate climate and fertile soil, this region is highly productive (Sagheb Talebi et al. 2014). The Hyrcanian forest is one of the last remnants of natural deciduous forest in the world. Native and endangered tree species include *Gleditschia caspica* Desf. (Caspian honey locust), *Pterocarya fraxinifolia* Land. (false walnut), *Parrotia persica* C.A.M. (Persian ironwood), *Zelkova carpinifolia* (Pall.) Dipp. (Siberian elm), *Buxus hyrcana* Pojark (box tree), *Populus caspica* Bornm. (Caspian poplar), and conifer species such as *Taxus baccata* L. (yew) and *Thuja orientalis* L. (oriental arbor-vitae) (Knapp 2005; Sagheb Talebi et al. 2014). Oriental beech (*Fagus orientalis*) is a major industrial species in the Hyrcanian forests, and beech forest (*Fagetum*) is the typical forest type at altitudes from 700 to 2000 m a.s.l.

The Hyrcanian forests are affected by construction of new roads, which clearly have irrefutable socioeconomic benefits, but may have negative impacts on the environment and ecosystem. To date, efforts have been made to understand, quantify, and where possible, offset the impacts of forest roads on adjacent ecosystems in the Hyrcanian forest (e.g., Lotfalian et al. 2012). However, there is currently no comprehensive study which analyzes the potential impact of forest roads on soil (e.g., N, P, K, C, and bulk density) and vegetation characteristics within the Hyrcanian forest, which are characteristics vital to a functioning ecosystem. The main aims of the current study are to estimate the size of the road-effect zone and to identify the main environmental changes due to forest roads. Specifically, we aim to evaluate the road-effects on: (1) the composition of herbaceous species and tree regeneration (up to 100 m distance from the forest road); (2) the light regime; and (3) soil properties, potentially related to changes in the ecosystem functions and composition. We hope that results will inform stakeholders in the decision-making process for new road construction projects, as well as maintaining old roads, while considering their effect on adjacent beech stands.

## Materials and methods

### Study area

The study was performed in the Kheyrud forest (Lat. 36°33'41"–36°33'51"N; Long. 50°33'14"–50°33'28"E; WGS84), which is located within the Hyrcanian forest, Northern Iran. Fifty-five years of meteorological records (1961–2015), measured by the meteorological station nearest to the study area (Nowshahr Meteorological Station: Lat. 36°39'N; Long. 51°30'E; 23 m a.s.l., 7 km from study area) characterized the mean annual precipitation as 1300 mm, with the heaviest precipitation occurring in the fall, with October and August as the wettest (average

235 mm) and driest (average 42 mm) months, respectively. The mean annual temperature was 17 °C, whereby February and August are the coldest (7.1 °C) and warmest (25.1 °C) months, respectively. The lithological substrate was mainly calcareous parent material (Anonymous 1995).

### Site selection

Data collection was performed close to forest roads in the Gorazbon (third) district of the Kheyroud forest. The Gorazbon district covers approximately 900 ha, and altitude ranges from 900 to 1400 m a.s.l. The road network of the district is classified as main forest roads with gravel surfacing. The road was constructed in 1988 with a width of 5.5 m and 8 km in length, and the road density in the district is about 8.9 m/ha. Forest roads within protective or non-logging regions (between 1100 and 1300 m a.s.l.) were selected for this experiment. These roads are constructed from native gravel (which has carbonate origin and is from the Kheyroud River), plus limestone for stabilization in some areas. Forest roads are mainly used by wood utilization vehicles, such as trucks and skidders, as well as other passenger cars.

### Vegetation sampling and analysis

Data were collected in summer 2015 (September) and spring 2016 (April). In total, 54 transects were constructed, with a minimum inter-transect distance of 30 m; 27 on up slope sides (the soil surface that remains above the road after material is removed) and 27 on down slope sides (the soil surface built below the road). A transect was composed of six plots (2 m × 1 m, whereby the longer edge of the plot ran parallel to the road edge), each of which was situated at 0, 10, 20, 30, 45, and 100 m, respectively, from the road edge (previous literature reports that excluding wind, most abiotic edge effects occur within 100 m distance to the road; Bignal et al. 2007; Delgado et al. 2007); thus, in total, there were 324 plots (162 plot per slope). To eliminate the effect of forest canopy, all transects were located in closed *Fagetum* forests, the dominant forest type in the Gorazbon district. Transects that included a 100-m continuous buffer on all sides to minimize the edge effects of other landscape features, such as large canopy gaps, or other roads, were selected for study (Watkins et al. 2003).

The proportions of life forms (Raunkiaer 1934) were determined at each plot in a transect. Raunkiaer (1934) proposed a life-form classification system based on the place of the buds during unfavorable seasons. According to this classification system, plant species can be divided into five main classes: phanerophytes (Ph), chamaephytes (Ch), hemicryptophytes (He), cryptophytes (Cr), and therophytes (Th). As there is no specific life-form class in Raunkiaer's original system for non-self-supporting plants, such species were

classified according to the reduction of their aerial parts, as described by Cain (1950). In this research, we used the Raunkiaer system to classify species, as life-form classification is characterized by plant adaptation to certain ecological conditions (Mera et al. 1999).

### Canopy cover and LAI measurements

At each plot, hemispherical photographs were taken with a 180° fish eye lens (Canon EF 8–15 mm f/4L) directed upward and attached to a Canon EOS 6D digital camera mounted on a leveling device (Sadeghi et al. 2017, 2018). Photographs were taken with exposure under conditions of diffuse skylight, soon after sunrise or immediately before sunset (Sadeghi et al. 2016, 2017), and were analyzed for canopy cover and LAI using Gap Light Analyzer software (GLA, Ver. 2) (Frazer et al. 1999). In each plot, we recorded frequency of herbaceous plant species on the forest floor. All plants were listed and identified using the guidebooks *Flora Orientalis* (Boissier 1867), *Flora of Turkey* (Davis 1942), and *Flora Iranica* (Rechinger 1963–1998).

### Soil sampling and analysis

Soil data were collected in summer 2015 (September). At each plot, one soil sample (about 2 kg) was collected at a depth of 10 cm below the surface (i.e., a depth of 0–10 cm; Olander et al. 1998; Rentch et al. 2005a, b). Soil samples were filtered through a sieve with a 2 mm aperture. Sand, silt, and clay ratio of soil samples was determined using Bouyoucos hydrometer method (Makineci et al. 2007). Bulk density, soil moisture, pH, and electrical conductivity (EC) values were measured. Soil bulk density was evaluated in steel cylinders of 10 cm length and 5 cm diameter (at a depth of 10 cm below the surface). Soil samples collected in the cylinders were then weighed, dried at 105 °C to constant mass, and finally weighed again to obtain dry bulk density. EC was determined using EC meter in a 1:2.5 soil: distilled water solution. Available P was determined with a spectrophotometer using the Olsen method (Homer and Pratt 1961), available Mg, Na, Ca, and K (by ammonium acetate extraction at pH 9) with an atomic absorption spectrophotometer, and cation exchange capacity (CEC) with a flame photometer (Bower et al. 1952). The percent of organic matter (OM %) was determined using the Walkley and Black wet digestion method loss on ignition and converted to a Walkley–Black equivalence (Walkley and Black 1934). pH was determined using a Mehlich buffer method with water (Mehlich 1976). Total N was obtained using the Kjeldahl–Lauro method (Bremner and Mulvaney 1982). All analyses were conducted in the laboratory of the Faculty of Natural Resources, University of Tehran.

## Statistical analysis

To identify the range of the road-effect zone and to detect between-plot differences in environmental conditions, we used principal component analysis (PCA). PCA plots in which ordinations cluster close together indicate comparable environmental conditions. To detect which environmental variables explain differences between plots, we calculated Pearson's correlations between the sample scores of the ordination and all environmental factors: LAI, canopy cover, pH, bulk density, soil moisture, EC, available Mg, available P, organic matter, C, total N, Na, available Ca, available K, and CEC. All environmental variables were standardized to account for different scales of measurement. Analyses were done using R 3.4.1 (R Core Team 2017).

To determine the effect of distance from the road on soil chemical properties and coverage by herbaceous species of a plot, we performed one-way analysis of variance (ANOVA). Tukey's honestly significant difference (HSD) tests were performed post hoc to identify pairs of soil chemical properties that were significantly different. Soil chemistry data were standardized to reach normal distribution. Confidence intervals were established at the 0.05 probability level, and all statistical analyses were performed in R 3.4.1.

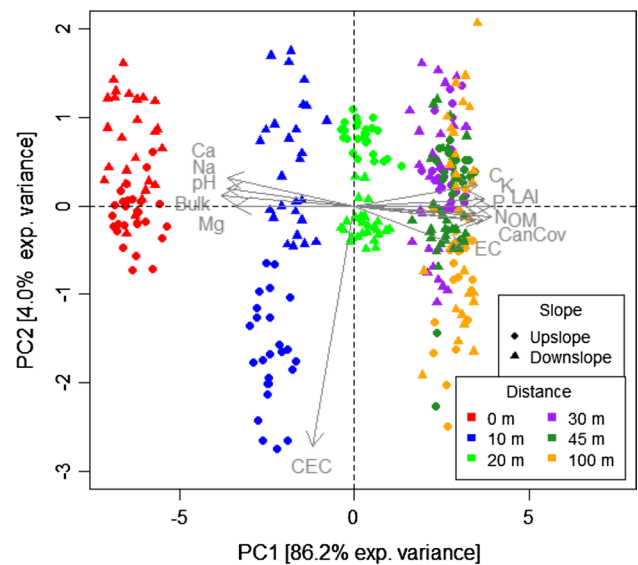
## Results

### PCA analysis

The PCA analysis (Fig. 1) demonstrates that environmental conditions did not significantly differ at plots located more than 30 m from the road edge, indicating that the road-effect zone boundary lies at approximately 30–45 m from the road edge. Furthermore, within the road-effect zone, the influence of the road on soil properties decreased as distance from the road increased; plots ordinated into distinct groups: 0, 10, or 20 m from the road (Fig. 1). The road-effect zone was unaffected by the direction of the land slope (except for CEC; Fig. 1), and consequently, up-slope and down-slope plots were combined for all subsequent analyses (Fig. 1).

### Road-effect on canopy cover and LAI

Stand parameters indicated that canopy cover and LAI were both positively correlated with distance from the road (Fig. 2). The lowest values of LAI and canopy cover (%) were observed at the road edge (0 m), whereas the highest one was observed at 100 m (Fig. 2). Based on results from HSD test, the LAI value at 100 m was significantly greater than at distances of 30, 20, 10, and 0 m from the road edge



**Fig. 1** PCA ordination diagram of the 324 plots (162 plots in up slope and 162 plots in down slope) characterized by 14 environmental parameters (Bulk: bulk density; OM: organic matter; CanCov: canopy cover). The plots are located at six different distances to the forest road. Significant correlations with the ordination axes are shown in gray (see Table S1 in the electronic appendix); dots refer to up-slope plots and triangles to down-slope plots

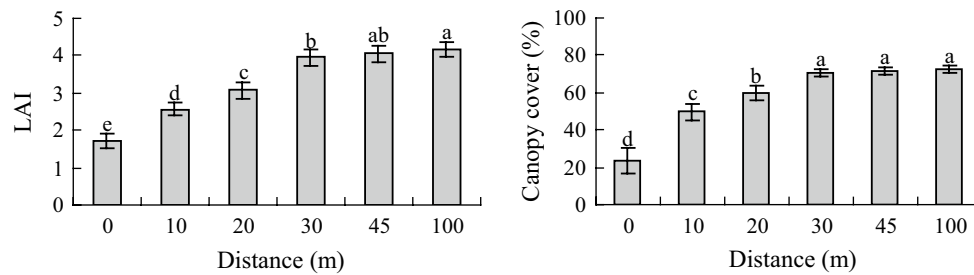
(Fig. 2). Also, the canopy cover (%) was significantly higher at distances of 100, 45, and 30 m compared to distances closer to the road ( $P < 0.05$ ; Fig. 2).

### Road-effect on soil properties

Concerning soil parameters, the highest base saturation of chemical properties (highest values of pH, greatest content of calcium, sodium, magnesium, and CEC) and the most compacted soils (highest bulk density) were situated closest to the road edge. Although these parameters were linearly correlated with distance from the road, distances of more than 30 m from the road edge were not significantly affected (Fig. 3). In contrast, the content of carbon, nitrogen, phosphate, potassium, and organic matter, and electrical conductivity all increased as distance from the road also increased (Fig. 3). CEC values at 0 m from the road were significantly greater than for other road distances (Fig. 3).

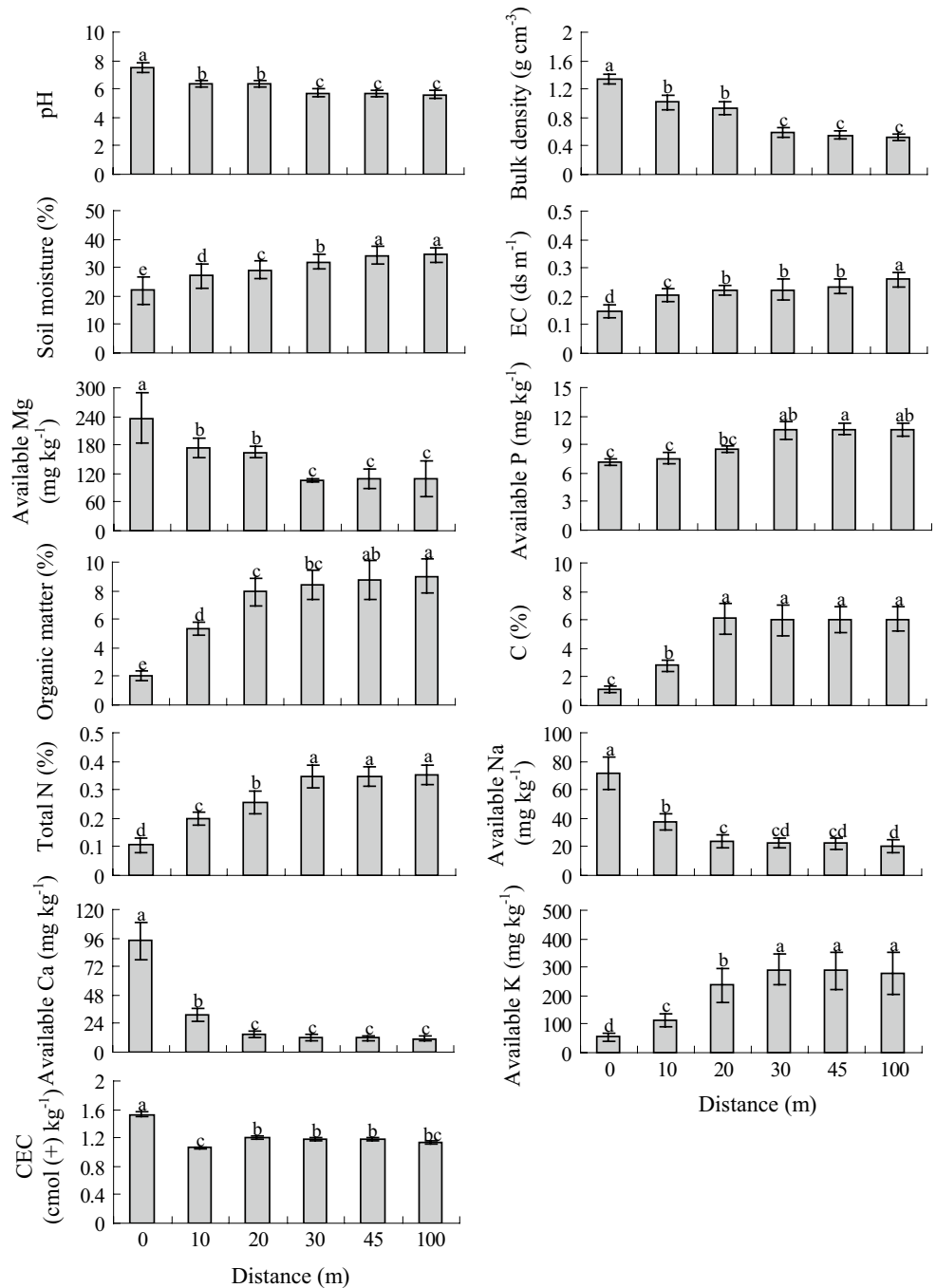
### Road-effect on plant life form

In total, 84 plant species belonging to 52 families were recorded across the 324 plots (Table 1), with the family *Poaceae* comprising the greatest number of species (7 species). Of the 52 families identified, 37 (71.1%) were each represented by only a single species. The Raunkiaer's life form of each plot showed a high proportion of cryptophytes (35.7%),



**Fig. 2** Leaf area index (LAI) and canopy cover (%) values in main forest roads (54 plots per distance)

**Fig. 3** Soil properties in main forest roads (54 plots per distance). Bars denote standard deviation (SD)



**Table 1** Family and floristic life form of identified plant species in Kheyroud Forest, north of Iran

No.	Family	Species	Life form
1	Aceraceae	<i>Acer cappadocicum</i> Gled.	Ph
2		<i>Acer velutinum</i> Boiss.	Ph
3	Adoxaceae	<i>Sambucus ebulus</i> L.	Cr
4		<i>Eryngium caucasicum</i> Trautiv.	He
5	Apiaceae	<i>Sanicula europaea</i> L.	He
6	Apocynaceae	<i>Vincetoxicum scabrum</i> L.	He
7	Aquifoliaceae	<i>Ilex spinigera</i> Loes.	Ph
8	Araceae	<i>Arum maculatum</i> L.	Cr
9	Araliaceae	<i>Hedera pastuchovii</i> Woron.	Ph
10	Asparagaceae	<i>Danae racemosa</i> (L.) Moench.	Ph
11	Aspleniaceae	<i>Asplenium adiantum-nigrum</i> L.	He
12		<i>Asplenium scolopendrium</i> L.	Cr
13	Asteraceae	<i>Lapsana communis</i> L.	He
14	Athyriaceae	<i>Athyrium filix-femina</i> (L.) Roth.	He
15	Berberidaceae	<i>Epimedium pinnatum</i> Fisch. in DC.	Cr
16	Betulaceae	<i>Carpinus betulus</i> L.	Ph
17		<i>Alnus subcordata</i> C. A. Mey.	Ph
18		<i>Alnus glutinosa</i> L. Gaertn.	Ph
19	Blechnaceae	<i>Blechnum spicant</i> L.	He
20	Brassicaceae	<i>Alliaria petiolata</i> (M.B.) Cavara and Grande.	He
21		<i>Dentaria bulbifera</i> L.	He
22	Caprifoliaceae	<i>Sambucus ebulus</i> L.	He
23	Compositae	<i>Willemetia tuberosa</i> Fisch. and C.A. Mey. ex DC.	He
24	Convolvulaceae	<i>Calystegia sepium</i> L.	Cr
25		<i>Festuca drymeia</i> Mert. and Koch in Roehling.	He
26	Crassulaceae	<i>Sedum stoloniferum</i> S.G. Gmel.	Ch
27	Cyperaceae	<i>Carex griolittii</i> Romer in Schkuhr.	Cr
28		<i>Carex remota</i> L.	He
29		<i>Carex strigosa</i> Hudson.	He
30		<i>Carex sylvatica</i> Hudson.	He
31	Dennstaedtiaceae	<i>Pteridium aquilinum</i> (L.) Kuhn.	Cr
32	Dryopteridaceae	<i>Dryopteris filix-mas</i> L.	Cr
33		<i>Polystichum aculeatum</i> (L.) Schott.	He
34	Ebenaceae	<i>Diospyros lotus</i> L.	Ph
35	Euphorbiaceae	<i>Mercurialis perenis</i> L.	Cr
36		<i>Euphorbia amygdaloides</i> L.	Ch
37	Fagaceae	<i>Fagus orientalis</i> Lipsky.	Ph
38		<i>Quercus castaneifolia</i> C.A. Mey.	Ph
39	Geraniaceae	<i>Geranium robertianum</i> L.	Th
40	Hamamelidaceae	<i>Parrotia persica</i> C.A. Meyer.	Ph
41	Hypericaceae	<i>Hypericum androsaemum</i> L.	Ph
42		<i>Hypericum perforatum</i> L.	He
43	Juncaceae	<i>Luzula forsteri</i> (Smith), DC. in Lam. and DC.	He
44	Lamiaceae	<i>Mentha aquatica</i> L.	Cr
45		<i>Prunella vulgaris</i> L.	He
46		<i>Scutellaria tournefortii</i> Benth.	He
47		<i>Salvia glutinosa</i> L.	He
48		<i>Lamium album</i> L.	Cr
49		<i>Lamium galeobdolon</i> L.	Cr
50	Malvaceae	<i>Tilia platyphyllos</i> Scop.	Ph
51	Moraceae	<i>Ficus carica</i> L.	Ph



**Table 1** (continued)

No.	Family	Species	Life form
52	Oleaceae	<i>Jasminum officinale</i> L.	Ch
53	Onagraceae	<i>Circaea lutetiana</i> L.	Cr
54	Ophioglossaceae	<i>Ophioglossum vulgatum</i> L.	Cr
55	Orchidaceae	<i>Platanthera bifolia</i> (L.) L. C. Rich.	Cr
56	Plantaginaceae	<i>Plantago major</i> L.	He
57		<i>Plantago lanceolata</i> L.	He
58	Poaceae	<i>Brachypodium sylvaticum</i> P. Beauv.	He
59		<i>Digitaria sanguinalis</i> Scop.	Th
60		<i>Festuca drymeia</i> Mert. and W.D.J. Koch.	Cr
61		<i>Paspalum dilatatum</i> Poir.	Cr
62		<i>Microstegium vimineum</i> (Trin.) A. Camus.	He
63		<i>Oplismenus undulatifolius</i> (Ard.) P. Beauv.	Th
64		<i>Poa nemoralis</i> L.	He
65	Polygonaceae	<i>Rumex sanguineus</i> L.	He
66	Primulaceae	<i>Cyclamen coum</i> Miller.	Cr
67	Pteridaceae	<i>Pteris cretica</i> L.	Cr
68		<i>Adiantum capillus-veneris</i> L.	Cr
69	Rhamnaceae	<i>Frangula alnus</i> Miller.	Ph
70	Rosaceae	<i>Crataegus microphylla</i> C. Koch.	Ph
71		<i>Mespilus germanica</i> L.	Ph
72		<i>Geum urbanum</i> L.	He
73		<i>Fragaria vesca</i> L.	He
74		<i>Rubus sanctus</i> Schreb.	Ph
75		<i>Rubus lanuginosus</i> Stev. ex Ser.	Ph
76	Rubiaceae	<i>Galium odoratum</i> (L.) Scop.	Cr
77	Ruscaceae	<i>Ruscus hyrcanus</i> Woron.	Ch
78	Salvianaceae	<i>Primula heterochroma</i> Stapf.	He
79	Smilacaceae	<i>Smilax excelsa</i> L.	Cr
80	Solanaceae	<i>Solanum kiesertzkii</i> C.A. Mey	Cr
81	Ulmaceae	<i>Ulmus glabra</i> L.	Ph
82	Urticaceae	<i>Urtica dioica</i> L.	He
83	Violaceae	<i>Viola alba</i> Bess. subsp. <i>Sintenisii</i> W. Becker.	He
84	Woodsiaceae	<i>Athyrium filic-femina</i> (L.) Roth.	Cr

Raunkiaer's life form: *Ph* phanerophyte, *Ch* chamaephyte, *He* hemicryptophyte, *Cr* cryptophyte, *Th* therophyte

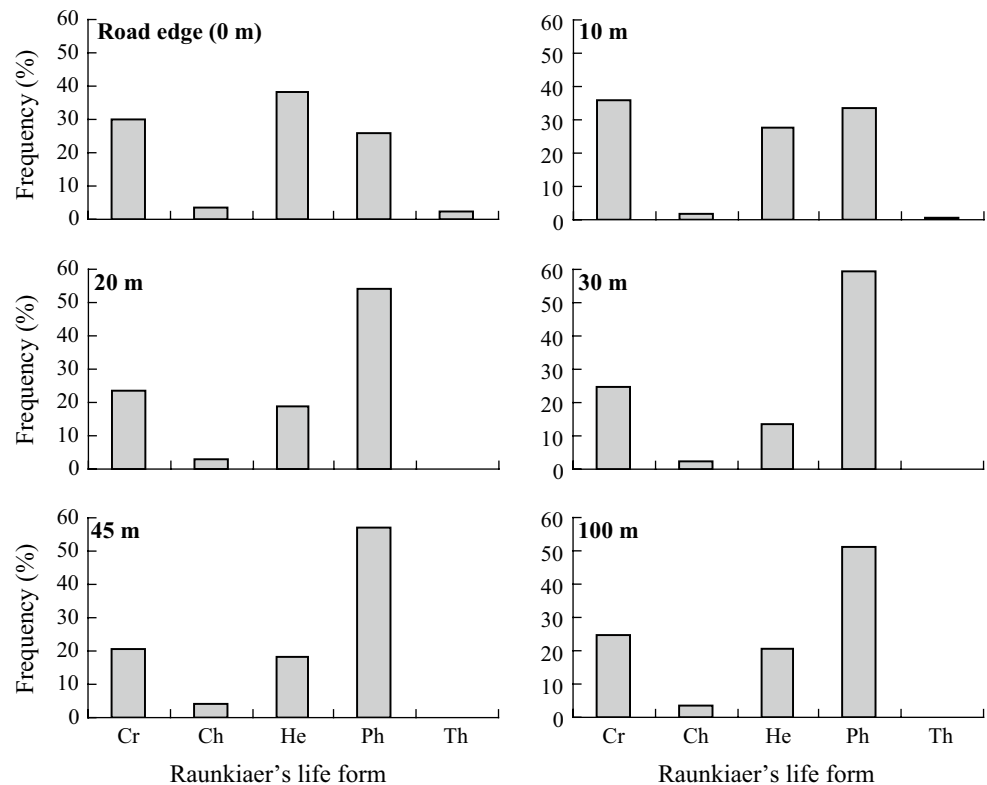
followed by hemicryptophyte (32.1%), phanerophytes (25%), chamaephyte (4.8%), and therophytes (4.8%) (Table 1).

The frequency of different life forms changed with distance from the road (Fig. 4). The vegetation at 0 m was dominated by cryptophytes, at 10 m by hemicryptophyte, and all distances greater than 10 m were dominated by phanerophytes (Fig. 4). The edge effect of roads was apparent up to 10 m from the road edge, and at greater distances, therophytes were no longer present (Fig. 4).

## Discussion

Our results indicate that in the study area, the boundary of the road-effect zone extends up to 30 m from the road edge. Within the road-effect zone, we observed a clear effect of the road on the vertical structure of the adjacent forests (represented by LAI and canopy cover percentage). Canopy cover is one of the most important factors that

**Fig. 4** Frequency of plant species Raunkiaer's life-form percent in different distances of main forest road



impacts microclimate (Metzger and Schultz 1984), and in the current study, canopy cover was higher at greater distances from the road, a pattern which has previously been reported in the literature (Watkins et al. 2003; Pauchard and Alaback 2006; Harper et al. 2007; Enoki et al. 2014). Opening the canopy due to deforestation associated with forest road construction can influence plant growth and competition patterns, especially between shade-tolerant and shade-intolerant species (Horn 1971; Planchais and Sinoquet 1998), which, in our study, was reflected by a decrease in LAI at plots close to the roads. A decrease in LAI results in an increase in light penetrating the canopy (Kucharik et al. 1999); hence, irradiation at the forest floor is lower at further distances from the road.

The role of soil moisture in determining plant species distributions and community structure has often been studied; some researchers have found that soil moisture is the best predictor of flora diversity (Härdtle et al. 2003; Pec et al. 2015; Wei et al. 2015), while others have observed that soil moisture has only a minor role in determining plant diversity (Vockenhuber et al. 2011). Some studies that have investigated soil moisture of plots close to roads in comparison with adjacent closed canopy stands have found that soil moisture is higher at plots more distant from the roads, due to increased transpiration and interception rates in the forest interior (e.g., Kapos 1989; Osmá et al. 2010; Li et al. 2010; Ma et al. 2014). However, other studies have

found that soil moisture is higher close to forest roads, which may be due to increased runoff that can occur along roads (Olander et al. 1998; Neher et al. 2013; Avon et al. 2013; Tarvirdizadeh et al. 2014). In our study, soil moisture was greater at the forest interior than at the road edge. The higher organic matter content, as well as shade from the forest, contributes to the higher soil moisture measured in the forest interior (Neher et al. 2013). We observed that, along roads, the canopy was more open; thus, light increased and the soil moisture content was reduced, especially on up slopes. This reduction was also clearly evident on down slopes, although the amount of light on such slopes was relatively lower than that of up slopes (Tarvirdizadeh et al. 2014).

Soil bulk density was conversely correlated with distance from the road, a pattern in agreement with the scientific literature on this topic (Olander et al. 1998). Bulk density, an indicator for soil compaction (Heninger et al. 2002), increases as a consequence of mechanized harvesting on forest roads or skid trails (Ampoorter et al. 2010; Naghdi et al. 2010). Roovers et al. (2004) demonstrated that the intensity of soil compaction was highly (negatively) correlated with species cover and composition. Soils can be compacted by trampling and trail use, which reduces water infiltration rates and increases runoff and erosion potential (Hill and Pickering 2006). Demir et al. (2007) and Makineci et al. (2007) showed that bulk density value on skid roads was higher than in undisturbed forest. Because of the compaction that occurs



on forest roads after road building, the fine soil weight and bulk density values are higher closer to the road edge. It is likely that differences in bulk density of soil near to the road observed in the current study are due to disturbances during road construction.

We observed that pH and Ca decreased, while EC increased with distance from the road. Levels of Ca relate to the breakdown of the road surface and distribution of road particles through dust (Lamont et al. 1994; Honnay et al. 2002; Bernhardt-Römermann et al. 2006; Lotfalian et al. 2012; Neher et al. 2013). Moreover, the geological origin of the material used for the road surface was calcareous, and thus, it seems logical that Ca concentrations were greatest near the road edge and that soil pH was more alkaline at closer proximity to the road (Auerbach et al. 1997; Olander et al. 1998; Honnay et al. 2002; Bernhardt-Römermann et al. 2006; Lee et al. 2012; Lotfalian et al. 2012; Avon et al. 2013; Neher et al. 2013). Some road dust originates from winter sand applications, but also from soil particles tracked from gravel roads to paved roads on tires (Forman et al. 2003). The accumulation of lime and clay substrates can also increase soil pH (Greenberg et al. 1997) and may result in decreased EC values (Safari et al. 2013). Safari et al. (2013) showed that EC values at forest roads were significantly lower than in the forest interior. Also, the dense canopy in the interior of a forest modifies rainfall chemistry and EC values of throughfall and stemflow in beech stands were found to be higher than EC values of rainfall in adjacent open areas (Abbasian et al. 2015; Ahmadi 2015).

Our results indicate that the content of total N, P, K, C, and OM increased with the distance from the road. Due to soil excavation or filling activity during road construction, humus-poor soil layers from formerly greater depths may have been moved to the surface (both in down and up slopes). This might explain the lower content of N, P, K, C, and OM close to the road. On the contrary, the higher vegetation density at greater distances from the road, indicated in our study area by higher LAI and canopy cover, causes more litter and hence more N (Cowling and Field 2003; Flechard et al. 2011), P (Cowling and Field 2003; Smethurst et al. 2003), K (Cowling and Field 2003), C (Coker 2006), and OM (Luo et al. 2004) in the soil. The higher LAI and canopy cover at greater distance from the road cause more comb-out of N, P, and K from the atmosphere. Increased denitrification rates close to the roadside may also reduce soil N if runoff from road surfaces results in waterlogged soil (Wilson et al. 1995). In our study, P concentration was lowest at plots close to the road and was therefore positively correlated with distance from the road edge, as has been previously reported (Honnay et al. 2002; Neher et al. 2013). The availability of soil nutrients, including P and K, is commonly reduced in roadside soils, due to soil compaction. Increased compaction of roadside soils may reduce decomposition, with

associated repercussions for nutrient cycling (Guariguata and Dupuy 1997; Bolling and Walker 2000). In our study, C and OM had the lowest values close to the road. As for N, higher LAI values, as well as a denser canopy cover, contributed to the higher levels of C and OM measured in the forest interior (Muskett and Jones 1981; Olander et al. 1998; Neher et al. 2013). Soil OM is a key ecosystem property that exerts control on secondary succession, water-holding capacity, hydraulic properties, and nutrient dynamics (Lloyd et al. 2013). We found the greatest content of available Mg (Honnay et al. 2002; Bernhardt-Römermann et al. 2006; Lotfalian et al. 2012) and Na (Bernhardt-Römermann et al. 2006; Neher et al. 2013) in soil close to the roads. This result is due to the calcareous geological origin of the gravel used for road construction, since road gravel is very likely the main source of dust that is deposited along the road. Soil from the road edges also had the greatest CEC values (e.g., Neher et al. 2013). On the road edge, we observed the highest proportion of clay (data not shown). Soil texture plays a key role in determining many soil chemical properties such as CEC, and soils with a high clay composition tend to have a higher CEC (Ashman and Puri 2002).

The higher values of available Mg compared to available Ca observed in the current study were somewhat surprising. We explain this uncommon result by the methods used during the extraction procedure: Mg was extracted by ammonium acetate extraction at high pH values (ammonium acetate buffers at soil pH 7.0) (Normandin et al. 1998). Thus, this method will only approximate CEC if the pH of the soil is 7.0 and otherwise can result in large overestimates of CEC in more acidic soils (Ross and Ketterings 1995). This is a clear limitation of our study; thus, we cannot interpret the absolute values of Mg. However, the observed pattern of comparative differences in Mg content at different distances from the road remains valid.

Our study demonstrates a constant decrease in the pioneer (therophyte life form) to shade-tolerant (phanerophyte life form) ratio as distance from the road edge increases. Ehren-dorfer (1965) suggested that perennial hemicryptophytes and annual therophytes represent adaptation to different types of pioneer habitats. Houssard et al. (1980) showed that therophytes are abundant in the first stages of succession, whereas phanerophytes are rare. As most therophyte species are light demanding, the increased penetration of light to the forest understorey is a key factor favoring such life forms (Godefroid and Koedam 2004; Deljouei et al. 2017b). Avon et al. (2013) state that phanerophytes and chamaephytes were absent from the roadside, but particularly frequent in the forest interior. Deljouei et al. (2017b) found that in a hornbeam-beech forest the edge effect of roads was apparent up to 5 m from the road edge, and at distances greater than this, chamaephytes did not exist, with the study site changing from largely phanerophyte species to hemicryptophytes.

Instead, Zielinska (2007) demonstrated that the highest percentage of therophytes was in close proximity to the forest road and hemicryptophytes were the highest Raunkiaer's life form, as in agreement with our findings.

## Conclusion

The road-effect zone in forest habitats extends for variable distances from the road edge, depending on the characteristic of the forest ecosystem under consideration. Our results indicate that, in the studied area, roads exert changes in soil properties, stand characteristics, and vegetation composition up to 30 m from the road edge. Landscape planners should be aware of the remarkable impacts of forest roads on the surrounding forest ecosystem. Due to the importance and uniqueness of Hyrcanian forests, we suggest that a thorough assessment of road-effects on all of the facets of the forest ecosystem should become a requirement for any road-related intervention. Moreover, we suggest that long-term monitoring of multiple aspects of biodiversity, such as wildlife, moss and lichen diversity, as well as community structure, should be considered when assessing the road-effect zone. This multifaceted approach would allow us to obtain a more complete cost–benefit analysis and to point out “no intervention zones,” whose protection should be prioritized, such as fragile young forests that are already prone to anthropogenic change. We hope that this study contributes toward sustainable planning, construction and maintenance of forest roads in the Hyrcanian forest ecosystems.

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