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Pervasive impacts of railway edge effects on edaphic parameters and vegetation distribution patterns

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ABSTRACT

Addressing the ecological impacts of transport corridors while planning any transport network is paramount for a better of understanding ecological processes, biodiversity distribution, and ecosystem resilience. Here, we evaluated the impacts of railway edges on edaphic parameters, plant diversity, and composition in the northwestern Himalaya as a function of perpendicular distance from the railway track. In 2014 and 2017, we sampled vegetation plots across 31 sites distributed along 119 km of the Kashmir railway to test the effect of railway tracks on edaphic and vegetative parameters in short-term periods. T-shaped plots were laid comprising four subplots, one parallel to the track and the other three perpendiculars to it. We adopted the Mountain Invasion Research Network road survey methodology for data collection. We found (i) an increasing trend in all soil parameters (electrical conductivity, salinity, organic carbon, available nitrogen, and available phosphorus), except pH, as the distance from the railway track increased; (ii) significant railway edge effects on the importance value index of plant growth forms, life span, nativity and taxonomic group across space (distance of plots from the track) and time (2014–2017); and (iii) a significant spatiotemporal railway edge effects on plant species composition. Our results are pioneering in showing that railway tracks crossing through different ecosystems alter the edaphic conditions, resulting in direct and indirect edge effects on key abiotic and biotic factors, which in turn impact the vegetation of the surrounding natural habitats on both sides of the railway track. Our study contributes toward a better understanding of the role of anthropogenic edges like railways on edaphic parameters and vegetation distribution.

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1. Introduction

In the current era of the Anthropocene, unbridled human activities are fast driving the linear clearings of the mountain landscapes (Laurance et al., 2009; Sur and Singh, 2020). Of the various changes caused by linear clearings in natural ecosystems, the edge impacts along the peripheral limit of the isolated habitat fragments are the most noticeable (Cerboncini et al., 2016). Edge effects can alter abiotic variables such as light, water availability, wind, temperature, nutrient concentration, and other variables, ultimately creating new microclimatic habitats that widely differ from the core (Reinmann and Hutyra, 2016; Ries et al., 2004). It is known that the creation of these edges can have a direct or indirect impact on the biodiversity and ecosystem processes, in which species can take advantage of the edges (positive effect) (Christianini and Oliveira, 2013; da Rosa et al., 2017), avoid the edges (negative effects) (Christianini and Oliveira, 2013; da Rosa et al., 2017; Mendonça et al., 2015), or in certain cases, no response (neutral effects) (Christianini and Oliveira, 2013). Although edge effects are commonly distributed worldwide, there still are some gaps in species-specific or site-specific effects by creating human-mediated artificial boundaries within vegetation.

The most common anthropogenic activity that leads to edge effects is the construction of transport networks such as railways and roads, enabling people to move and thus connect communities and economies (Havlick, 2002; Penone et al., 2012; Rashid et al., 2021). Impacts from edges can have physical and ecological consequences, such as changes to soil and vegetation parameters (Meza-Elizalde and Armenteras-Pascual, 2021). Edges formed by linear clearings for human infrastructure like railways for a small amount of habitat clearing significantly increase edge exposure within intact habitats (Van Der Ree et al., 2015; Penone et al., 2012). Furthermore, edge effects are frequently more severe when fragments are small or irregularly shaped (Laurance and Yensen, 1991), and the impact of edges depends on the width of the habitat clearing (Lucas et al., 2017; Barrientos and Borda-de-Água, 2017). However, railways and roads pose challenges in the management and conservation of different types of ecosystems as transport systems serve as the drivers of several environmental problems like habitat fragmentation, wildlife road kills and act as dispersal agents of invasive alien plants (Forman et al., 2003; Haq et al., 2021). The railway edges are highly disturbed habitats owing to initial construction activities and recurrent movement of men and machinery along railway tracks, and this favours the invasion by certain alien species, ultimately resulting in the displacement of native flora (Hansen and Clevenger, 2005; Pauchard and Alaback, 2004). In addition, the disturbed habitats along the railway edges are moderately homogeneous in climatic and edaphic variables, favouring alien invasion (Wilson and Aebischer, 1995; Waheed and Arshad, 2024). The construction of railway lines alters microclimatic conditions due to changes in the physical variables such as edaphic factors, moisture, temperature, wind regimes, and light (Forman et al., 2003; Murcia, 1995). The impacts of railways are not only limited to the edges and the surrounding area but also range from a few meters to several hundreds of meters well into the natural landscapes in the hinterland (Bergès et al., 2013; Forman et al., 2003; Otto et al., 2014).

In Kashmir Himalaya, a mountainous region northwest of the Indian Himalayan Region, a railway track has been recently constructed and has been operational since October 2009 (Fig. 1). From an ecological perspective, the railway track provides an ideal natural experimental system to investigate the edge effects of railway on the edaphic properties, plant species diversity, composition and distribution patterns, with wide implications for biodiversity conservation and ecosystem management. To our best knowledge, no such study describing the edge effects of railway tracks in the Himalaya has been carried out till now. To address this knowledge gap, this study was undertaken by sampling T-shaped transects perpendicular to the railway line in the Kashmir Himalaya (Figs. 2 and 3), following the road survey methodology of the Mountain Invasion Research Network (MIREN) (Kueffer et al., 2014). Here, we evaluated the spatiotemporal impacts of railway edge effects on edaphic parameters and plant diversity and composition in the Kashmir Himalaya, India.

The study aimed to assess the influence of railway tracks on vegetation and soil indicators, which was done using sample plots laid near and away from the railway tracks. Comparing the observation of plots "near to" and "away from" railway tracks indicated the influence of the track on the parameters analyzed. The assessment over two repeated times (years 2014 and 2017) will show short-term variation in edaphic and vegetation parameters. The laying down of railway tracks disturbed the nearby area from where soil materials are used for elevating the railway track. The area near the track initially lacked vegetation cover, which increases once moving further away and perpendicular from the track. Thus, we hypothesized that areas close to the track have different abiotic and biotic parameters compared to the faraway areas. To test this, we assessed: (i) how railway edge effects influence soil parameters (pH, electrical conductivity, salinity, organic carbon, available nitrogen, and phosphorus)? (ii) How do railway edge effects influence the importance value index of different plant growth forms, life spans, nativity, and taxonomic groups? And, (iii) how do railway edge effects influence the importance value index of native and non-native species? Overall, this study builds toward a better understanding of the role of anthropogenic edges like railways on abiotic factors and vegetation communities.

2. Methods

2.1. Study area

The study was carried out along the Kashmir railway (the only railway line of the region) that starts from Baramulla on the northwestern edge of the Kashmir valley passing through Pir Panjal railway tunnel connecting south and southwest Bichleri valley of Banihal through Qazigund area of the Kashmir valley (Fig. 1). Lying between coordinates of 32°20′ to 34° 50′ N and 73° 55′ to 75° 35' E, the region is spread over an area of 15,948 km^2, with nearly 64% of the total area being mountainous (Fig. 1). The surrounding habitat of the railway line is a mosaic of natural ecosystems, croplands (paddy fields) and plantations. The altitude of the valley plain at Srinagar is 1600 m above sea level (masl). The temperature ranges from an average daily maximum of 31^{o}C and a minimum of 15^{o}C during summer to an average daily maximum of 4^{o}C and a minimum of –4^{o}C during winter. It receives annual precipitation of about

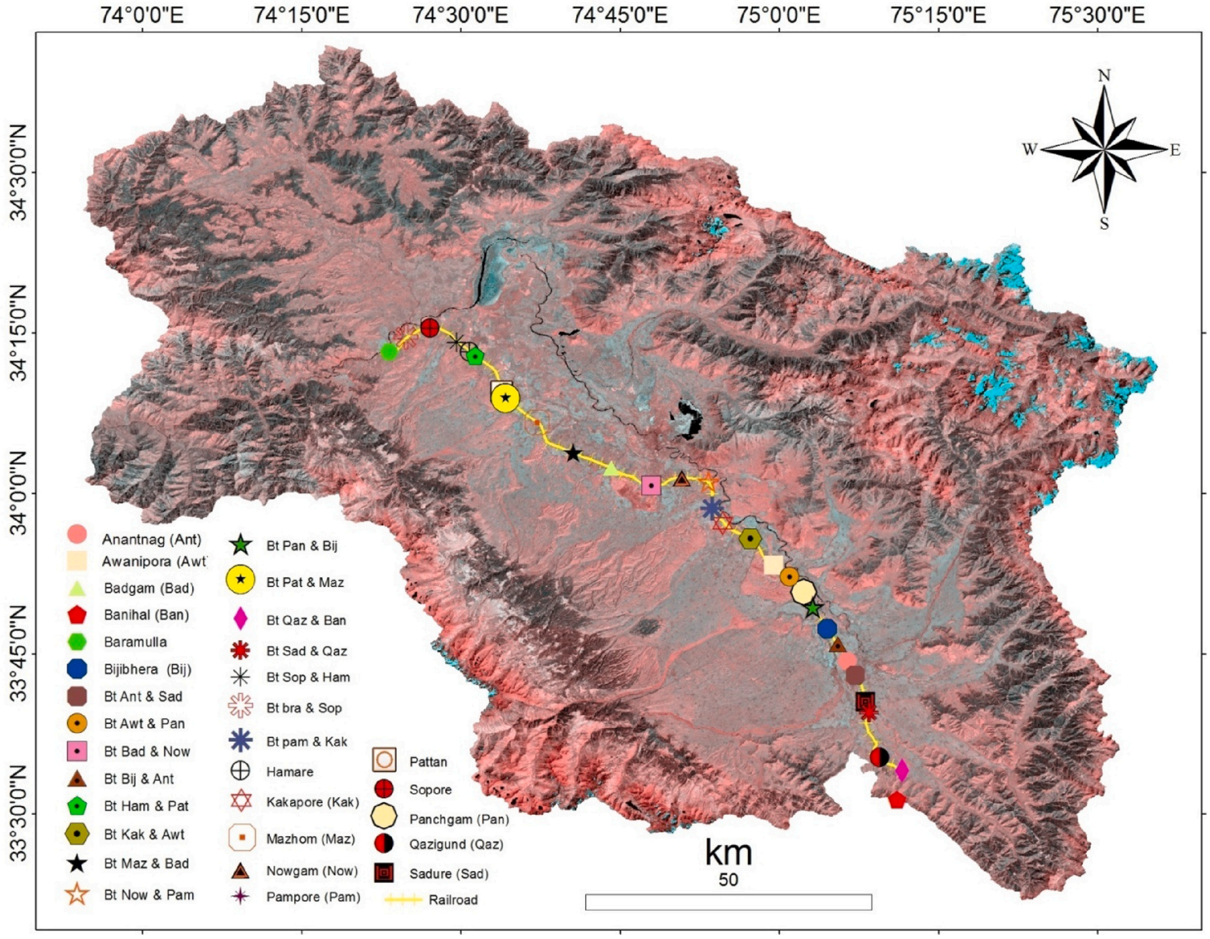

Fig. 1. – Map of the study area showing the Kashmir railway, with 31 sampling sites, of which 16 were stations and 15 were between stations. Between stations, sites are represented by the letters "Bt" before the names.

1050 mm, mostly snow during winter (Series, 2021). The region is marked by peculiar seasonality, with four well-defined seasons: winter (November–February), spring (March–May), summer (June–August), and autumn (September–November) (Rashid et al., 2021).

The Kashmir Railway Project was started to provide an alternative and reliable transportation system to land-locked Kashmir. It is a

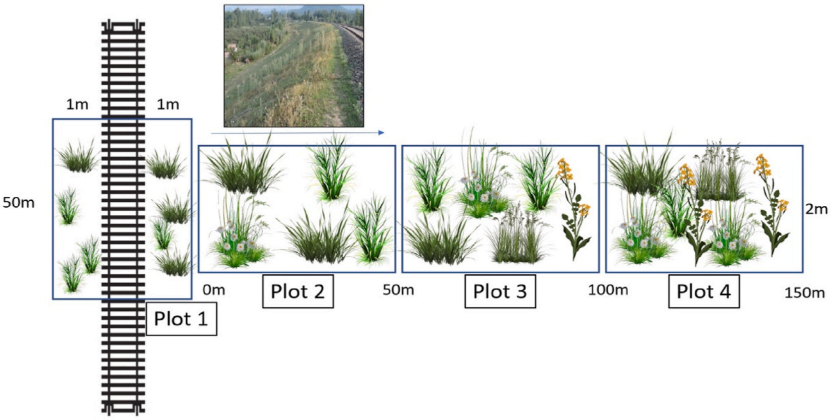

Fig. 2. Schematic representation of sampling plots. The first plot (Plot 1) was laid parallel and close to the train track, whereas the other three plots (Plot 2, Plot 3, and Plot 4) were laid perpendicular to the track. Each plot was of the same size (2 × 50 m).

Fig. 3. Schematic photographic representation of sampling plots. (a) Plot 1 (Track) (b) Plot 2 (Embankment) (c) Plot 3 (Mainland-1) (d) Plot 4 (Mainland-2).

345 km long railway line linking the Kashmir Valley to the rest of India and is the biggest project undertaken by Indian Railways since the country's independence in 1947. Officially called the Jammu-Udhampur-Katra-Quazigund-Baramulla link (JUSBRL), the railway line has been under construction since 1994. The project was given the status of a national project in 2002. The initial deadline was for 2009; however, various delays pushed it to 2012 and extended to 2017. There are 31 stations, all built following the Indian standard broad track gauge of width 1.676 m and laid on concrete sleepers.

2.2. Data collection

This study was carried out along the Leg 3 section of the Kashmir railway project, which comprises 119 km and was completed in October 2009. The stretch was divided into 31 sites: 16 stations and 15 between-station sites (Fig. 1). The between-station sites were selected as midpoints between the stations. The minimal distance between the sampling sites was 13 km. The upper surface of the railway track, which is raised from the adjacent mainland (except Budgam and Qazigund Stations), was flat and raised through an embankment. At each site, four plots (each of size 2 × 50 m) were laid, with one plot parallel to the track edge and the other three plots perpendicular to it, forming the letter 'T'. The head of the 'T' (hereafter "P1") was parallel and closest to the railway track. The remaining three plots were perpendicular to the track with 0–50 m (hereafter "P2"), 50–100 m (hereafter "P3"), and 100–150 m (hereafter "P4") away from the railway track (Figs. 2 and 3). To test the hypothesis that railway track influences both abiotic and biotic variables, we evaluated the variation of soil and vegetation parameters in each plot (P1 to P4). Any significant effect of railway tracks on vegetation and soil can be tested by comparing plot differences. Due to the difficulty in establishing control plots (i.e., to what extent we still observe edge effects), we just compared soil and vegetation parameters among plots the.

Field survey and sampling were carried out from March to November during four periods: initial sampling in 2014 and resampling in 2017, the 5th and 8th year after the railway project was finished. We recorded the GPS coordinates at each site and marked the sampling locations with tags for data collection. In addition, at each sampling site, we recorded the name/number of the railway signposts/poles to establish permanent sampling plots for future data collection. Within each plot (P1, P2, P3, and P4), three 1 m^2 sub-plots were laid to quantify species abundance and diversity and study soil-related parameters. Soil parameters were evaluated only in 2017 due to logistic issues. The three subplots in each plot were equally distributed along the 50m (0m, 25m, and 50m). The enumeration was done over the four distinct seasons in a year, making 48 sub-plot observations (12 sub-plots x 4 seasons = 48 observations) for one site. The importantly, land use and weather conitions were almost similar over the two assessment periods, 2014 and 2017.

A total of 31 sites throughout 119 km were sampled, making total observations for 1488 subplots in a year (48 subplots x 31 sampling locations = 1488 subplots). Assessment in the year 2017 was done in the same plots. Observations over distinct seasons help identify certain species (flowering/fruiting period), while the appearance of a few species (mainly forbs) is also seasonal. The standard taxonomic procedure was followed to collect voucher plant specimens for identification and further studies (Haq et al., 2019). The standard herbarium methods were used to preserve the obtained plant specimens, including drying, preserving, labelling, and pasting them onto herbarium sheets (Bridson and Forman, 2010). The voucher specimens were placed in the University of Kashmir Herbarium (KASH-2018), with field data recorded on the herbarium sheets. The plant species were classified into families using APG-IV (Meerow, 2023).

After collecting specimens, we categorized plant species according to their (i) growth form (grass, forbs, and vines), (ii) life span (annual, biennial and perennial), (iii) nativity (exotic and native), and (iv) taxonomic group (pteridophytes, monocotyledonous, dicotyledonous) (Haq et al., 2023). Each species' growth form was classified as grass, forbs, and vines, depending on the direction, size, and amount of branching of the main shoot axis or axes (Perez-Harguindeguy et al., 2013). With abundance, cover, and number of species from each quadrant (frequency), we calculated the importance value index (hereafter IVI) for each plant species per plot per site per year. The abundance for all species was computed by dividing the number of plots that contained the species by the total number of plots laid in the study area. We calculated the IVI for each plant species as combined observation over a year, including pooled seasonal data. We used the IVI because it is a standard ecological tool to measure the dominance of plant species in an ecosystem (Waheed et al., 2023).

From each plot (P1, P2, P3, and P4), three different random soil samples from the top 30 cm depth were collected in the year 2017 to study the different physiochemical parameters of the soil. Soil samples were taken within the three randomly selected 1 × 1m plots in each main plot (P1-P4). Soil samples from each plot were taken and sieved via a 2 mm mesh screen. The pH was calculated using a pH meter (1 part of the soil to 5 of distilled water; Mettler Toledo pH meter), and electrical conductivity and salinity were calculated

Table 1

– Model statistics for the railway edge effects on different abiotic (soil) and biotic (plant) parameters between years (2014 and 2017) and plots (P1 – 0 m, P2 – 50 m, P3 – 100 m, P4 – 150 m) along railway line in Kashmir Himalaya, India. IVI – Important Value Index. LR – Likelihood-Ratio. SD – Standard deviation.

Analysis	Response	Fixed effects	LR or Wald test	*P*-value	Random effects	Variance
Soil parameters	pH	Plot	13.894	0.0030	Site	0.0354
	Electrical Conductivity (μS/cm)	Plot	29.384	0.0001	Site	984
	Salinity (ppm)	Plot	27.834	0.0001	Site	133
	Nitrogen (kg/ha)	Plot	25.047	0.0001	Site	426.8
	Organic Carbon (%)	Plot	46.443	0.0001	Site	0.0061
	Phosphorus (μg/g)	Plot	13.863	0.0031	Site	0.0118
Growth form	Grass (sqrt(IVI+1))	Plot	274.268	0.0001	Site: Year	2.105e-01
		Year	30.544	0.0001	Year	1.067e-09
		Plot: Year	27.892	0.0001		
	Forbs (sqrt(IVI+1))	Plot	523.443	0.0001	Site: Year	2.373e-01
		Year	0.532	0.4655	Year	5.662e-10
		Plot: Year	106.499	0.0001		
	Vines (IVI)	Plot	154.952	0.0001	Site: Year	4.526e-02
		Year	3.242	0.0717	Year	1.515e-07
		Plot: Year	4.615	0.2022		
Life span	Annual (IVI)	Plot	213.902	0.0001	Site: Year	6.965
		Year	14.272	0.0001	Year	8.890e-08
		Plot: Year	57.882	0.0001		
	Biennial (IVI)	Plot	80.975	0.0001	Site: Year	7.043e-02
		Year	0.540	0.4621	Year	3.185e-10
		Plot: Year	10.522	0.0146		
	Perennial (IVI)	Plot	244.203	0.0001	Site: Year	4.822e+01
		Year	28.261	0.0001	Year	4.386e-07
		Plot: Year	37.336	0.0001		
Nativity	Exotic (IVI)	Plot	194.846	0.0001	Site: Year	1.097
		Year	55.827	0.0001	Year	7.673e-08
		Plot: Year	73.613	0.0001		
	Native (IVI)	Plot	362.635	0.0001	Site: Year	6.109e+01
		Year	34.030	0.0001	Year	2.387e-04
		Plot: Year	53.512	0.0001		
Taxonomic Group	Pteridophytes (IVI)	Plot	0.335	0.9532	Site: Year	3.476e-01
		Year	0.251	0.6162	Year	1.186e-08
		Plot: Year	5.124	0.1629		
	Monocotyledonous (IVI)	Plot	293.767	0.0001	Site: Year	3.201e+01
		Year	12.400	0.0001	Year	3.158e-07
		Plot: Year	36.568	0.0001		
	Dicotyledonous (IVI)	Plot	246.934	0.0001	Site: Year	2.569e+01
		Year	0.005	0.9404	Year	5.467e-05
		Plot: Year	55.247	0.0001		

using an electrometer (Conductivity TDS Tester - HI98129) (Haq et al., 2022). The total nitrogen was estimated using the modified Kjeldahl method, phosphorous using Olsen's method, and carbon using the Walkley and Black method (Gupta 2017).

2.3. Data analysis

All analyses were conducted in R 4.0.0 (R Core Team, 2020). We evaluated the model fit by checking residual distribution with Q-Q plots, histograms, and boxplots.

2.3.1. Soil parameters

To compare the variation of soil parameters (pH, electrical conductivity, salinity, organic carbon, available nitrogen, and available phosphorus) between plots (P1, P2, P3, and P4), we used a Linear Model (LM) followed by Likelihood-Ratio Test (LRT) using the packages "stats" (R Core Team, 2021) and "car" (Fox and Weisberg, 2019), respectively. We averaged the values per plot before conducting the analysis. Soil parameters were fit as the response variable, and plots were fit as the predictor variable (Table 1). We also added the site as a random effect to control the spatial dependence of plots. Pairwise comparisons were assessed by estimated marginal means (Lenth, 2020).

2.3.2. Plant diversity parameters

To analyze the edge effects of the railway on different parameters of plant diversity across spatial and temporal scales, we conducted a Linear Mixed Model (LMM) using Template Model Builder followed by Wald's test with the packages "glmmTMB" (Brooks

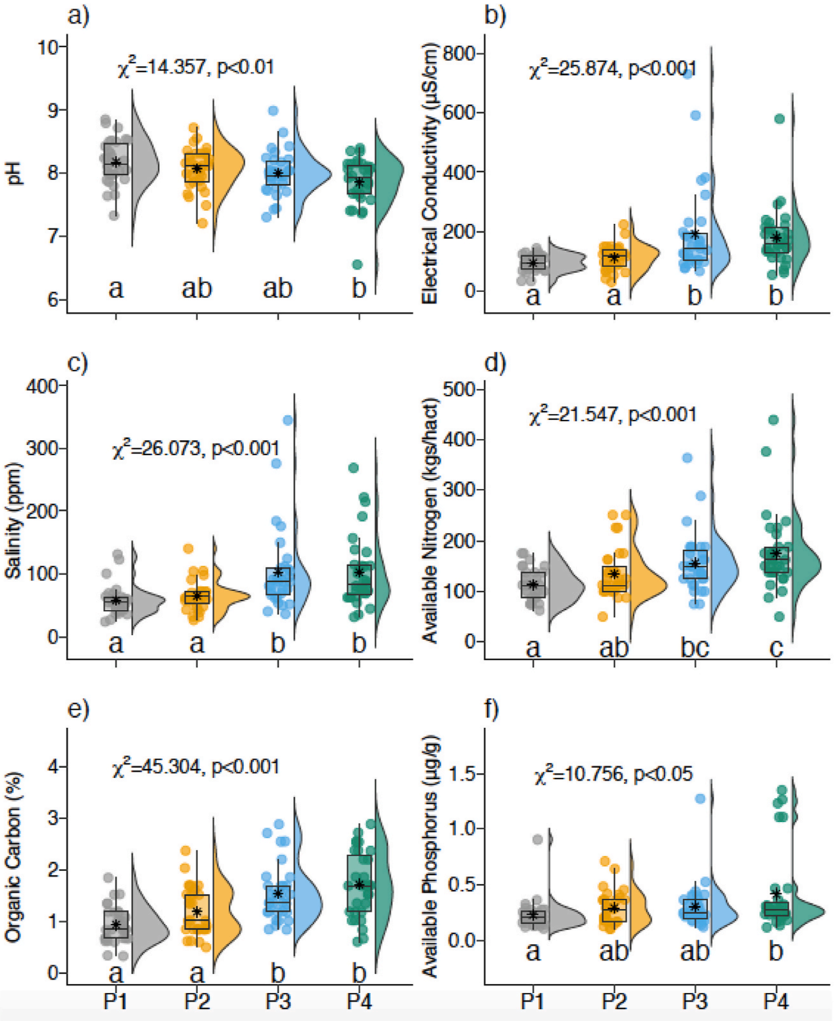

Fig. 4. – Railway edge effects on soil parameters at 0 m (P1), 0–50 m (P2), 50–100 m (P3), and 100–150 m (P4) from the railway line. Statistical analyses are represented by the Likelihood-Ratio Test (Table 1). Different letters differ from each other by estimated marginal means. Asterisks within the boxplots represent the mean value. Boxplots and kernel density function represent figures.

et al., 2017) and “car”, respectively. We used the IVI of each plant species as the response variable and the interaction between the year of sampling (2014 and 2017) and the plots evaluated (P1, P2, P3, and P4) as predictor variables (Table 1). We also added a site nested within a year (1|*site/year*) as a random factor to control temporal and spatial repeated measures. If significant, we conducted an estimated marginal means as pairwise comparisons. In the case of grasses and forbs, we transformed the data using the formula sqrt (x+1) to account for heteroscedasticity. Other growth forms (trees and shrubs) were found, but we excluded them from further analysis due to the low data available.

2.3.3. *Species composition*

The presence/absence data was used to evaluate whether the species composition changes in short-term periods (~year), and as the perpendicular distance from the railway track increases (~Plots), we used an NMDS (Non-multidimensional scaling) ordination method followed by a PERMANOVA (Permutational Multivariate Analysis of Variance) with Euclidean distance and 999 permutations (pseudo-F ratios). After PERMANOVA, we ran pairwise comparisons of the interaction between years and plots with corrections for multiple testing, using Euclidean distance and 999 permutations. False discovery rate (FDR) was used as the p-value adjustment method. PERMANOVA and pairwise comparisons were conducted using the package “RVAideMemoire” (Hervé, 2020). Further, we observed the contribution of each plant species to overall dissimilarities. For that, we used a similarity percentage analysis, a *simper(.)* function, based on the decomposition of overall dissimilarity in the package “vegan” (Oksanen et al., 2019).

3. Results

3.1. *Soil parameters*

We found a significant difference in all soil parameters (pH, electrical conductivity, salinity, organic carbon, available nitrogen, and phosphorus) between plots (P1, P2, P3, and P4) (Fig. 4; Tables 1 and 2). All soil parameters, except pH, showed an increasing trend as the distance from the railway line increased. Our pairwise comparisons using estimated marginal means showed that P3 and P4 plots did not differ from each other for any parameter (*p-value* ratio: 0.231–1.000; Fig. 4); however, these two plots (P3 and P4) significantly differ from P1 and P2 plots for all parameters, except pH and Phosphorous, where only P4 differed from P1 (Table 2; Fig. 4).

3.2. *Plant diversity parameters*

Considering the growth form, we found a significant interaction between the effects of plots (spatial effect) and years (temporal effect) on the IVI of grasses (Table 1, Fig. 5a) and forbs (Table 1, Fig. 5b) but not for vines (Table 1, Fig. 5c). Further, simple mean effects analysis showed that the IVI of grasses was significantly influenced by both plots and years (Table 1, Fig. 5a). The P1 plots showed the lowest values of IVI of grasses and P2 and P3 the highest. Temporally, the IVI of grasses significantly increased from 2014 to 2017 (Table 3). In the case of forbs, simple mean effects showed that plots significantly influenced the IVI of forbs, but not by years (Table 1, Fig. 5b). The P2 plots in 2014 had the highest value and were different from all other plots in both years (2014 and 2017) (Table 3). Again, P1 plots had the lowest values, and P3 and P4 showed intermediate values. P4 plot increased the number of forbs from 2014 to 2017. For vines, we only observed a significant difference in the IVI between plots, where P1 plots showed the highest values.

For life span, we found a significant interaction between the effects of plots and sampling years on the IVI of three types of life span: annual (Table 1, Fig. 6a), biennial (Table 1, Fig. 6b), and perennial (Table 1, Fig. 6c). Simple main effects analysis showed that the IVI of annual plants was significantly influenced by both plots and years (Table 1, Fig. 6a). P1 plots in both years showed the lowest values of IVI and P2 plots in 2014 had the highest values. Only the IVI of annual plants of P2 plots significantly decreased from 2014 to 2017 (Table 3, Fig. 6a). In the case of biennial plants, simple mean effects showed that plots significantly influenced the IVI, but not by year of sampling (Table 1, Fig. 6b). P2 plots in both years had the highest values compared to the other plots, but showed no difference between years. Finally, a simple mean effects analysis showed that the IVI of perennial plants was significantly influenced by both plots and years (Table 1, Fig. 6c). P1 in both years showed the lowest values. P2 had the highest values and did no change between the years. P3 and P4 significantly increased the IVI 2017 (Table 3, Fig. 6c).

We found a significant interaction between the effects of plots and years on the IVI of exotic (Table 1, Fig. 7a) and native (Table 1, Fig. 7b) plants. A simple analysis of the mean effects showed that the IVI of both exotic and native plants was also significantly influenced by both plots and years (Table 1, Fig. 7a–b). Considering exotic plants, P2 had the highest values in both years. However, it

Table 2
– Mean (±sd) values of railway edge effects on soil parameters at 0 m (P1), 50 m (P2), 100 m (P3), and 150 m (P4) from the railway line.

Soil parameters	Plots			
	P1	P2	P3	P4
pH	8.2 ± 0.4	8.1 ± 0.3	8 ± 0.3	7.9 ± 0.4
Electrical Conductivity (μS/cm)	95.9 ± 27.8	113.9 ± 42.3	192.3 ± 149.2	180.5 ± 96.1
Salinity (ppm)	57.8 ± 24	65 ± 23.9	103.4 ± 65.8	102.9 ± 56.7
Nitrogen (kg/ha)	113.7 ± 31.1	134.7 ± 48.6	156.2 ± 59.1	175.2 ± 76.2
Organic Carbon (%)	0.9 ± 0.3	1.2 ± 0.5	1.5 ± 0.5	1.7 ± 0.6
Phosphorus (μg/g)	0.2 ± 0.1	0.3 ± 0.2	0.3 ± 0.2	0.4 ± 0.4

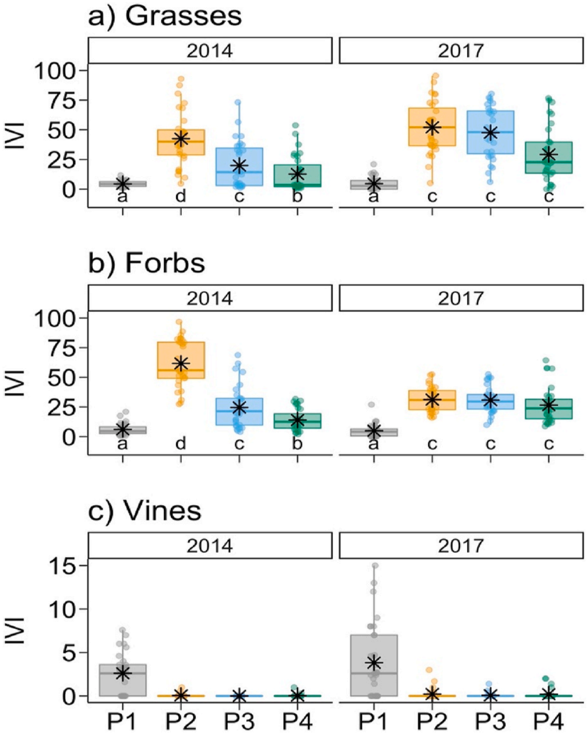

Fig. 5. – Railway edge effects on the importance value index (IVI) of different plant growth forms – grasses (a), forbs (b), and vines (c) – at 0 m (P1), 50 m (P2), 100 m (P3), and 150 m (P4) from the railway during 2014 and 2017. Statistical analyses are represented by the Wald Test (Table 1). Different letters differ from each other by estimated marginal means. Asterisks within the boxplots represent the mean value.

Table 3
– Important Value Index (IVI) average (±sd) of railway edge effects on plant diversity parameters at spatial distances of 0 m (P1), 50 m (P2), 100 m (P3), and 150 m (P4) from the railway line during sampling years of 2014 and 2017.

Plant parameters	2014				2017			
	P1	P2	P3	P4	P1	P2	P3	P4
Species richness	6.1 ± 2.3	26.2 ± 6.2	14.38 ± 5.2	12.06 ± 4.1	3.0 ± 0.7	13.7 ± 2.2	10.3 ± 1.9	8.9 ± 2.9
Growth form								
Grass	4.4 ± 2.6	42.5 ± 22.6	19.9 ± 19.2	12.7 ± 14.9	4.6 ± 5.3	52 ± 21.6	47.6 ± 21.1	29.2 ± 23
Forbs	6.1 ± 4.9	64.8 ± 22.9	24.6 ± 17.7	14 ± 9.2	4.9 ± 5.6	31.2 ± 10.4	30.8 ± 11.2	26.6 ± 15.2
Vines	2.6 ± 2.3	0.1 ± 0.2	0 ± 0	0.1 ± 0.2	3.8 ± 4.3	0.2 ± 0.6	0.1 ± 0.3	0.2 ± 0.6
Life span								
Annual	2.7 ± 2.6	42.7 ± 20.8	15 ± 12.3	10.6 ± 10.5	2.2 ± 3.8	18.5 ± 9	14.7 ± 12.4	12.1 ± 10.1
Biennial	0.1 ± 0.2	1.9 ± 1.4	0.3 ± 0.9	0.3 ± 0.7	0.3 ± 1.6	1.1 ± 1.3	0.3 ± 0.5	0.3 ± 0.7
Perennial	10.3 ± 4.9	62.3 ± 27.3	28.9 ± 24	15.2 ± 16.5	10.9 ± 9.8	64 ± 21	63.4 ± 28.4	43.5 ± 25.3
Nativity								
Exotic	6.8 ± 4.3	38.9 ± 18.6	11.9 ± 11.4	8.5 ± 8.7	6.6 ± 5.2	13.1 ± 6.5	5.6 ± 4.8	5.1 ± 6.3
Native	6.3 ± 2.9	69.7 ± 27	32.7 ± 25.2	18.4 ± 18.3	6.8 ± 5.8	70.5 ± 22.2	72.9 ± 28	50.9 ± 24.7
Taxonomic group								
Pteridophytes	0.3 ± 0.7	1.5 ± 8.3	0.1 ± 0.3	0.1 ± 0.5	0.6 ± 3.2	0 ± 0	1 ± 3.4	1.4 ± 4.9
Monocotyledonous	4.5 ± 2.6	61.6 ± 30.6	20.9 ± 19.4	13.4 ± 14.7	4.6 ± 5.3	54.4 ± 21.3	48.5 ± 20.4	30.8 ± 21.9
Dicotyledonous	0.3 ± 0.7	1.5 ± 8.3	0.1 ± 0.3	0.1 ± 0.5	0.6 ± 3.2	0 ± 0	1 ± 3.4	1.4 ± 4.9

significantly decreased in 2017 (Table 3, Fig. 7a). In the case of native plants, P1 in both years had the lowest values, and P2 had the highest values, not changing between years (Table 3, Fig. 7b). On the other hand, the IVI of native plants on P3 and P4 plots significantly increased between years (Table 3, Fig. 7b).

Considering the taxonomic group, we did find a significant interaction between the effects of plots and years on the IVI of monocotyledonous (Table 1, Fig. 8a) and dicotyledonous (Table 1, Fig. 8b). Simple mean effects analysis showed that the IVI of monocotyledonous was significantly influenced by both factors (plots and years; Table 1, Fig. 8a). P2 plots had the highest values of IVI but did not change between years (Table 3, Fig. 8a). P3 and P4 plots significantly increased in 2017 (Table 3, Fig. 8a). The IVI of dicotyledonous was significantly influenced by plots, but not years (Table 1, Fig. 8b). The P1 plots in both years had the lowest values,

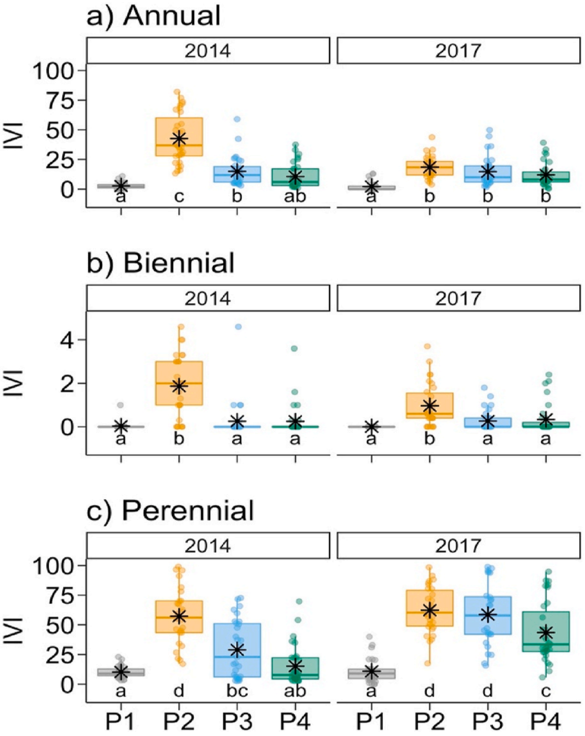

Fig. 6. – Railway edge effects on the importance value index (IVI) of different plant life spans – annual (a), biennial (b), and perennial (c) – at 0 m (P1), 50 m (P2), 100 m (P3), and 150 m (P4) from the railway line in 2014 and 2017. Statistical analyses are represented by the Wald Test (Table 1). Different letters differ from each other by estimated marginal means. Asterisks within the boxplots represent the mean value.

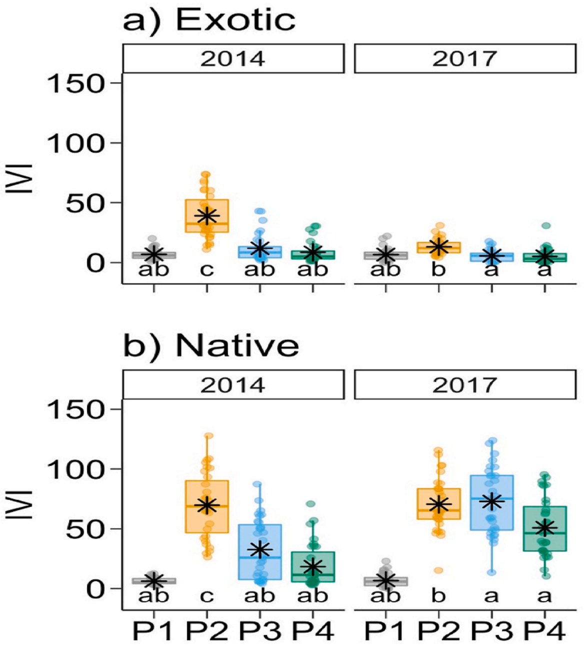

Fig. 7. – Railway edge effects on the importance value index (IVI) of different plant nativity – exotic (a) and native (b) – at 0 m (P1), 50 m (P2), 100 m (P3), and 150 m (P4) from the railway line in 2014 and 2017. Statistical analyses are represented by the Wald Test (Table 1). Different letters differ from each other by estimated marginal means. Asterisks within the boxplots represent the mean value.

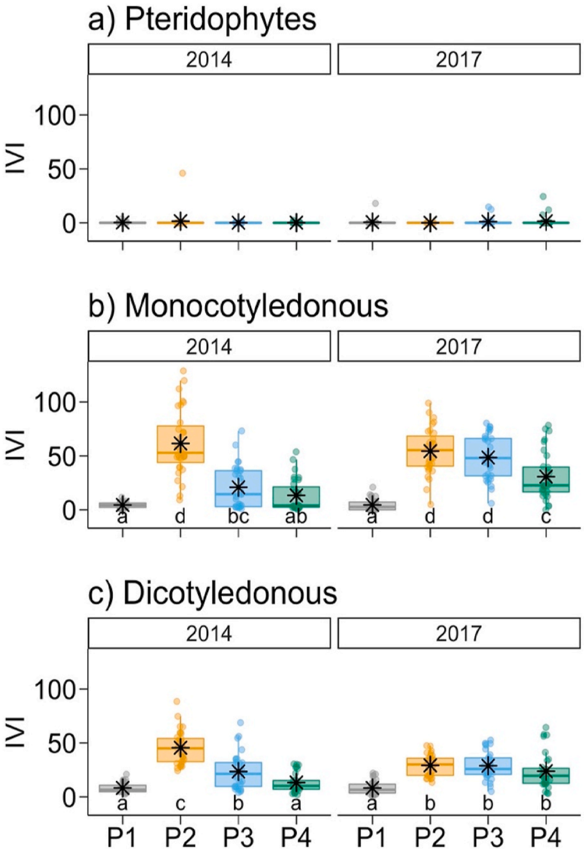

Fig. 8. – Railway edge effects on the importance value index (IVI) of different plant taxonomic groups – pteridophytes (a), monocotyledonous (b), and dicotyledonous (c) – at 0 m (P1), 50 m (P2), 100 m (P3), and 150 m (P4) distance plots from the railway line in 2014 and 2017. Statistical analyses are represented by the Wald Test (Table 1). Different letters differ from each other by estimated marginal means. Asterisks within the boxplots represent the mean value.

but P2 plots had the highest value in 2014, significantly decreasing in 2017 (Table 3, Fig. 8b). On the other hand, P3 plots showed intermediate values, not changing between years, while P4 plots significantly increased in 2017 (Table 3, Fig. 8b).

3.3. Species composition

We observed a significant interaction between the effects of plots (spatial effects) and years (temporal effects) on plant species composition (Table 4, Fig. 9). All combinations of the interaction between plots and years (plots: year) differed from each other, except P1 plots in 2014 and 2017, which had a similar species composition (Table 5, Fig. 9). According to our contrast table of the contribution of individual plant species to the overall Bray-Curtis dissimilarity of species between the interaction of plots and years (plots: years) (Supplementay material Table 1), we identified nine plant species that most contributed to the overall dissimilarity, namely *Anthemis cotula, Avena sativa, Bromus japonicus, Convolvulus arvensis, Cynodon dactylon, Geranium rotundifolium, Mentha longifolia, Setaria viridis,* and *Trifolium repens*, represented by grasses and forbs.

4. Discussion

Linear infrastructure is expanding globally, but its impacts on ecological functions and processes within the landscapes must be more adequately understood and consequently inadequately mitigated (Nyumba et al., 2021). Thus, comparing multi-indicators of vegetation and environmental variables could be valuable in evaluating the mechanisms of ecological processes that cause biodiversity trends (Huang et al., 2021, 2024). The present study assessed the pervasive impacts of railway edge effects on edaphic factors and vegetation species diversity in the Kashmir Himalaya. We found (i) a significant difference in all soil parameters (pH, electrical conductivity, salinity, organic carbon, available nitrogen, and phosphorus) between plots, in which all parameters but pH showed a tendency to increase as the distance from the railway line increased; (ii) that there are significant spatial (variation between plots) and temporal (variation between years) railway edge effects on the IVI of plant growth form, life span, nativity and taxonomic group, where the effects are contingent on the specific division within each of these four vegetation parameters evaluated; and (iii) a

Table 4
– PERMANOVA results comparing species composition between the interaction of plots and years (plot: year). This analysis was made with Euclidean distance and 999 permutations. Pairwise comparisons are depicted in Table 5.

	Df	Sums of Sqs	Mean Sqs	F	R^2	Pr(>F)
Year: Plot	7	98608	14086.9	23.253	0.40412	0.001
Residuals	240	145398	605.8		0.59588	
Total	247	244006			1.000	

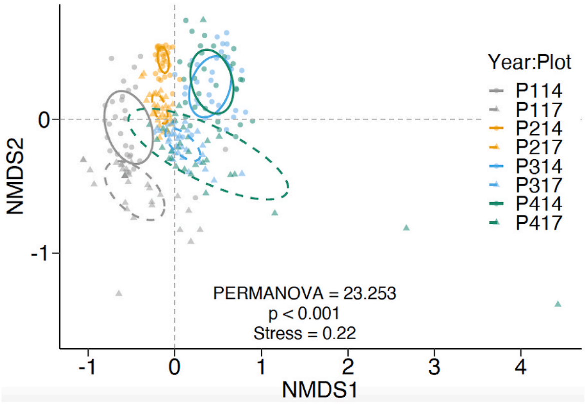

Fig. 9. – Non-Multidimensional Scaling (NMDS) followed by Permutational Multivariate Analysis of Variance (PERMANOVA) with 999 permutations and Euclidian distance evaluating the influence of railway edge effects on plant species composition in time (years: 2014 and 2017) and space (plots: P1, P2, P3, and P4). The P1, P2, P3, and P4 plots are 0 m, 50 m, 100 m, and 150 m from the railway line, respectively. The P114 (as for the other combinations) is the combination of plot (P1) plus year (2014 = 14). Results are depicted in Tables 4 and 5

Table 5
– Pairwise comparisons with FDR p-value adjustment method of plant species composition between the interaction of plots and years (Plot: Year) after PERMANOVA analysis (Table 4). Analyses were based on Euclidean distance and 999 permutations. The P114 (as for the other combinations) is the combination of plot (P1) plus year (2014 = 14 and 2017 = 17). P1, P2, P3, and P4 are 0 m, 50 m, 100 m, and 150 m from the railway.

	P114	P117	P214	P217	P314	P317	P414
P117	0.4540	–	–	–	–	–	–
P214	0.0013	0.0013	–	–	–	–	–
P217	0.0013	0.0013	0.0013	–	–	–	–
P314	0.0013	0.0013	0.0013	0.0013	–	–	–
P317	0.0013	0.0013	0.0013	0.0248	0.0013	–	–
P414	0.0024	0.0013	0.0013	0.0013	0.0146	0.0013	–
P417	0.0013	0.0013	0.0013	0.0013	0.0394	0.0047	0.0013

significant spatiotemporal (plot*year) railway edge effects on plant species composition, in which all combinations of plots and years differed from each other, except P1 in 2014 and 2017. Edge effects are physical and biotic changes at the edges of linear clearings (Cerboncini et al., 2016; Meza-Elizalde and Armenteras-Pascual, 2021). Edge-related changes in vegetation dynamics and microclimate have been observed worldwide (MacFarlane, 2003; Pohlman et al., 2009; Van Der Ree et al., 2015; Cardelús et al., 2020). As a result, these edges may become more prevalent in the future, and knowing their influence on vegetation will be crucial for effective biodiversity management alongside railway edges.

We found that as the perpendicular distance from the railway track increased, all soil parameters, except pH, tended to increase. The type of landscape structure between the railway and the surrounding natural areas is a potential reason for this result. As the distance from the railway track increases, different abiotic and biotic factors influence edaphic parameters (Bergès et al., 2013). Studying edge effects on soil parameters in French forests, Bergès et al. (2013) also observed significant variation of edaphic parameters over a gradient of ~1000 m. For instance, they observed a significant decrease in pH as the distance from the edge increases. Overall, studies have shown that the artificial edges created due to disturbance caused by the construction of roads and railways have significant variations in soil parameters, changing nutrient concentrations (Auerbach et al., 1997; Trombulak and Frissell, 2000), which can indirectly affect native biota.

We found significant spatiotemporal (plot*year) railway edge effects on the IVI of grass and forbs but not vines. Evaluating the effects of a road on the abundance of grass species in heathland vegetation in the UK, Angold (1997) observed a significant increase of grass species near the road, which can be potentially related to the concentration of oxides of nitrogen in these areas and to the relative competitive ability of grasses under conditions of eutrophication (Bobbink et al., 1992). In our study, the IVI of forbs showed a different trend from the grasses. The IVI of forbs was significantly influenced by plots rather than by years. A similar trend was observed by Sullivan et al. (2009), who reported that herbaceous species are predominant along the sides of transport networks (here P2) because in highly disturbed habitats, the forbs, mostly non-native and invasive species, complete their life cycle in a limited period for growth. We observed that soil from different areas for constructing P2 acts as a rich reservoir of seedbanks of different herbaceous species. Railway tracks represent a hard substratum habitat with stones and gravel, which is suitable for the growth of vines (Májeková et al., 2014), explaining the high IVI value of these habitats. The spread of the vines along railway transport is also reported in Europe (Jehlík et al., 2017; Kostrakiewicz-Gierałt et al., 2022).

The simple mean effects showed that plots and years have both positive and negative effects on the IVI of plants, considering their life span. The positive effect of railway edge on IVI is evident only for the perennial life span as we move away from the railway track (increase in IVI in P3 and P4) and over time (increase in 2017). A significant negative relationship between time and space on the IVI of annuals was observed along the railway line and over the years for P2. Perennial plants live for several years, often for decades, increasing canopy area, decreasing available light, and decreasing available nutrients, leading to a competitive environment for diverse plant assemblages such as annuals (Naeem et al., 2000). Also, perennial plant growth is a barrier to weed growth (Barker and Reynolds, 1999). For instance, perennial seed mixes can reduce weed problems at the edge by space preemption and competition, decreasing the potential establishment of other species (Marshall and Moonen, 2002).

In line with the previous points, the IVI of plants considering nativity (exotic or native) was also significantly influenced by railway edge effects in time and space (Fig. 6). The IVI of native species on P2, P3, and P4 moved closer to each other in 2017, potentially due to a decrease in exotic species IVI on P2 and no variation on P3 and P4. Studying the road edge effect patterns of native and exotic plants on an oceanic island, Otto et al. (2014) observed that exotic species are dominant in the edge band, and it decreases species richness. However, the same study showed different results for native plants compared to our study. Like the findings, Brothers and Spingarn (1992) argued that the considerable decrease in exotic species was due to dispersal constraints and that dense vegetation on the edge prevented exotic species from establishing. Furthermore, the plants' physical architecture or the community's permeability to the invasive inflow could be the initial predictor of whether an invasion is effective (Golivets, 2014). In some ecosystems, the richness of native plants increases, while in others, it decreases as the distance from the road edge increases (Otto et al., 2014). At the regional scale, differences in the traits of exotic and native species are likely to reflect differentiation in micro-habitat affinity (e.g. anthropogenic environments) or climatic tolerances (e.g. warm lowland regions) rather than the ways that coexisting and directly competing plants differ in the resources that they use (Ackerly et al., 2006). This view is supported by analyses of taxonomic similarity, which reveal greater differentiation between exotics and natives at community than regional scales (Diez et al., 2008; Lambdon et al., 2008; Heneidy et al., 2021).

In addition, these results suggest that biotic homogenization in the native species pool was increased by components of the railway edge, including those that promote patch connectivity and species exchange. Still, the high contribution of vegetation on railway lines to homogenization in the native species pool may indicate dispersal limitation, which led to a reduced species pool in plots located in surrounding natural areas (Trentanovi et al., 2013). Consistent with the results, Cerboncini et al. (2016) contended that the extent of the linear clearing in the landscape typically determines the substantial decrease in the influence of edges, which increases with distance from the railway track. Our findings confirmed that the impact of edge effects is influenced by the width of the clearing, with narrower clearings being less prone to edge-related disruption than wider linear clearings (Eldegard et al., 2015). The species richness pattern of exotic plants significantly decreased with distance to the railway track along all the sites of the railway line (Otto et al., 2014). Exotic species IVI was higher for P2 than P3 and P4, as Mwangi et al. (2007) showed. Therefore, results from comparable studies have demonstrated that other environmental factors are also essential in driving the composition and distribution patterns of plants along edges, in addition to the influence of railway edge effects in space and time on native and exotic plants, as demonstrated in our study (Penone et al., 2012). We found significant spatiotemporal railway edge effects on the IVI of monocotyledonous and dicotyledonous but not of pteridophytes (Fig. 7). We expected a low presence and variation of pteridophytes between the plots and years since the reproduction of these plants takes place in a cycle of alternation of generations dependent on water, which is only present during periods of precipitation and does not necessarily guarantee the reproduction of individuals (Raven et al., 2012). On the other hand, the railway line acts as the natural habitat, enhancing the dominance of monocotyledonous or clonal plants with a wide environmental distribution range in the landscape (Daz and Cabido, 1997; Petchey and Gaston, 2002). P2 had the highest values of IVI in 2014 and 2017 for both monocotyledonous and dicotyledonous, but a considerable increase of the IVI in P3 and P4 in 2017. This high value of IVI in P2 can be explained by the vegetation composition in these environments and the type of seed dispersion. The main groups of plants present in these regions (P2) were grasses and forbs. These plants have a high affinity with open areas and a strong relationship with the wind since their seeds are dispersed by the wind, making up the main plant species groups inside the edges (Winter et al., 2010; Son et al., 2024). In addition, over time (in our case, three years), we observed a considerable increase in the IVI of monocotyledonous and dicotyledonous in P3 and P4, which may be a temporal response to the spread of seeds of these more representative grass species and their competitive ability to explore and establish themselves in new habitats (Marshall and Moonen, 2002). Railway edges enhanced habitat heterogeneity through new habitat availability at the margins and unique microclimate conditions, increasing the ruderal plants' richness and abundance (Frenkel, 1977; Tikka et al., 2001).

Finally, we observed a significant interaction between the effects of plots (spatial effects) and years (temporal effects) on species composition (Table 4, Fig. 9). The colonization of these habitats around edges is largely determined by the environmental heterogeneity within and among the patches which can lead to differential filtering of species based on their ecological attributes (i.e. functional traits) (Chase, 2005; Mcgill et al., 2006; Püttker et al., 2015; Violle et al., 2007). Hence, if a species pool is functionally different, local community composition in heterogeneous patches should depend on immigration–extinction dynamics and trait-based environmental filtering (Matthews and Whittaker, 2014; McGill, 2010). As regions close to railway tracks (P2) are more resource-rich than the tracks (P1), resource availability can drive the presence of different plant communities even along shorter distances (Huston, 2004). Between tracks, on the other hand, continuous disturbance by passing trains might keep the system permanently in a very early stage of succession, in which higher species richness cannot be supported, explaining the plant composition similarity between P1 in both years.

5. Conclusion

Our results pioneer the idea that constructing railway tracks crisscrossing through different ecosystems can lead to direct and indirect edge effects on different physical and biological factors that impact the species composition along a railway track in the mountainous region of Kashmir Himalaya. The disturbance caused by the construction of railway tracks creates conditions that favour the growth of a few ruderal species, resulting in the formation of homogenous stands of non-native species. Therefore, performing an environmental impact assessment of the area through which the track passes is important to understand better the influence such artificial edges have on the species composition. Further, it is important to use local soil materials in creating track embankments because local soil favours local vegetation and hosts seed banks of local species. The results of our study suggest that before going for any construction work, especially the creation of roads or railway tracks, it is important to assess the track surroundings to devise plans to mitigate the loss to ecosystems and native biota. Thus, preventive measures or mitigating strategies should be used to prevent the loss triggered by the fragmentation of diverse ecosystems caused by the creation of artificial edges.

CRediT authorship contribution statement

Shiekh Marifatul Haq: Writing – original draft, Resources, Formal analysis, Data curation, Conceptualization. **Eduardo Soares Calixto:** Writing – review & editing, Visualization, Validation, Software, Methodology, Investigation. **Liang Song:** Writing – review & editing, Funding acquisition, Formal analysis. **Irfan Rashid:** Writing – review & editing, Supervision, Resources, Data curation. **Anzar Ahmad Khuroo:** Supervision, Conceptualization, Validation, Resources, Data curation, Writing – review & editing.

Declaration of competing interest

On behalf of coauthors, I declare that the authors have no conflict of interest regarding this manuscript.

Data availability

Data utilized for the research is provided as Tables/Figures in Appendix A as Supplemental Data.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envdev.2024.101064.

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