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Original Article

Impacts of road on plant invasions in the Middle Mountain region of central Nepal

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Abstract: Biological invasion is triggered by human development activities such as the construction and expansion of road networks. Road verges serve as important habitats and corridors for the distribution of invasive alien plant species (IAPS) between geographically distant habitats. However, the trajectory of plant invasion and the data regarding the impact of roads on IAPS distribution are relatively poor in Nepal. Here, we surveyed two road types (main roads and feeder road) in the Middle Mountain region of central Nepal in order to investigate how different road types are driving the dispersal of IAPS along road verges and the adjacent natural habitats. Systematic sampling was conducted at *ca* 2.5 km intervals along the roads. At each sampling site, paired plots (25 m × 4 m) were sampled: one adjacent to and along the road, and another 20 m away and parallel to it in the interior habitat. Our results revealed that the main road verges had a higher cover (33%) and a larger number of IAPS (14 species) than the feeder road (25%; 10 species). The IAPS cover and richness were significantly higher along verges than in the adjacent interior habitats for both road types, indicating that roads are contributing as corridors for the dispersal of IAPS in the Middle Mountain areas of central Nepal. Further, elevation, tree canopy, and disturbances (grazing/mowing/trampling) were found to be the key factors that determine spatial distribution of IAPS along road verges. We emphasize that regular monitoring of vegetation along the road verges can help with the early detection and control of potential IAPS in the region before they become problematic.

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1 Introduction

Road network is a common and expanding infrastructure in most landscapes with variety of cascading impacts on terrestrial and aquatic ecosystems and their functions (Trombulak and Frissell 2000; Coffin 2007). The ecological impacts of roads include road fatalities, habitat loss, the formation of barriers to animal dispersal and gene flow, as well as altered habitat structure, microclimate, edge formation, pollution, changes to hydrological processes, and increased susceptibility to biological invasions (Forman and Alexander 1998; Coffin 2007).

Disturbance associated with road construction and uses promote higher growth of disturbance-tolerant species such as the invasive alien plant species (IAPS) along road verges than the surrounding undisturbed habitats (Hansen and Clevenger 2005). Additionally, anthropogenic activities, including habitat modification and changes in land-use patterns, might further facilitate the establishment of alien species (Richardson and Pyšek 2006). However, establishment of the introduced species may be limited by extent of their propagule pressure (Hallett 2006). Many recent studies have investigated the factors contributing to the spread and establishment of alien species in the introduced range (Seipel et al. 2012; Lembrechts et al. 2014; Haider et al. 2018; Lázaro-Lobo and Ervin 2019). And, these studies have referred roads as a major corridor for the introduction and dispersal of invasive alien plant species within the introduced range (Spellerberg 1998; Parendes and Jones 2000; Pauchard and Alaback 2004; Foxcroft et al. 2019).

When compared to adjacent habitat, road verges have uniquely different environmental conditions in terms of soil texture, compaction, light availability, surface water runoff, and repeated maintenance (Gelbard and Belnap 2003; Hansen and Clevenger 2005). As a result of sudden changes in abiotic environments, road verges can alter species composition and have a species-specific impact on plant communities (Forman et al. 2003). The IAPS can tolerate better than native species to those environmental conditions and continue spreading to adjacent habitats upon their establishment on road verges (Pauchard and Alaback 2004). Thus, the cover and richness of IAPS are generally higher along road verges than in adjacent habitats (Pauchard et al. 2009). A number of factors, including road type (paved, unpaved, or earthen), traffic intensity, extent of road maintenance, and disturbance frequency influence plant invasion in the given area (Mortensen et al. 2009; Joly et al. 2011). Some studies have also highlighted a critical role of vehicles in the dispersal of IAPS (Forman et al. 2002; Ansong and Pickering 2013), and the large number of vehicles crossing biogeographic boundaries significantly increase IAPS propagule pressure on the road verges (Von Der Lippe and Kowarik 2007).

Due to the extreme climatic conditions and lower level of anthropogenic disturbances, mountain regions are often thought to have a relatively low risk of biological invasion. However, a growing number of evidences has revealed that a high number of IAPS have already been introduced in mountain landscapes (Pauchard et al. 2009; McDougall et al. 2011; Paiaro et al. 2011), and Nepal Himalaya is no more an exception. Located at the center of the Himalayan biodiversity hotspot (Mittermeier et al. 2011), Nepal Himalaya is under high threats from biological invasions (Paini et al. 2016) but has low national capacity to manage IAPS (Early et al. 2016). The higher difference in topography, the high dependency on international trade, the rapid changes in land-use pattern (e.g. agriculture land abandonment, urbanization) as well as habitat modification, and climatic changes have accelerated the spatial expansion of IAPS in Nepal (Shrestha et al. 2018; Shrestha 2019). A total of 182 exotic plant species belonging to 49 families and 129 genera have been reported from Nepal (Shrestha and Shrestha 2021). Among them, 28 species (15%) are invasive (Shrestha et al. 2021; Adhikari et al. 2022), with a wide range of impacts on the general environment, including agriculture production and human well-being (Shrestha 2019; Shrestha et al. 2019a). While several IAPS have already established in the Middle Mountain regions of Nepal, only a few IAPS have been reported from the High Mountains, notably *Ageratina adenophora*, *Bidens pilosa*, *Galinsoga quadriradiata*, and *Parthenium hysterophorus* (Shrestha et al. 2019b).

The road network in Nepal is still inadequate, considering its development needs. Nevertheless, Nepal has a higher road density than other mountainous South Asian countries like Bhutan and Pakistan (Sudmeier-Rieux et al. 2019). For the past two decades, construction of roads has been the main priority of the government in many parts of the world (Rankin et al. 2017). The local rural roads in Nepal experienced a 1200% rise over this period of nearly two decades of time, from 4780 km in 1998 to 57,632 km in 2016 (DoLIDAR 2016), which is likely to continue at a faster pace in the coming decades. Opening of new roads has increased highland-lowland interconnectedness. As a result, high mountain regions requiring week long trek are now accessible through one-day drive. These roads can drive various changes in the mountain ecosystems (Laurance et al. 2009), including habitat fragmentation (Delgado et al. 2007), pollution (Karmakar et al. 2021) and rapid spread of the IAPS (Shrestha et al. 2019b). As roads often provide ideal conditions for IAPS to establish, grow, and spread (Trombulak and Frissell 2000; Hansen and

Clevenger 2005), increasing road network is likely to increase threats of plant invasions in the mountain regions of Nepal. However, the impacts of road on IAPS establishment have been rarely studied in Nepal. In this study, we aimed to 1) compare diversity and abundance of the IAPS along road verges and the nearest relatively undisturbed habitats in the Middle Mountain region of central Nepal, 2) understand the impacts of road types on plant invasions, and 3) identify factors governing the IAPS diversity and abundance on road verges. Results of this study have provided empirical evidences on the role of road network in facilitating plant invasions in the study area and highlighted the need of monitoring vegetation along road verges for the prevention and control of IAPS.

2 Methods

2.1 Study area

The study area included three districts, namely Gorkha, Tanahun and Lamjung, located in the Middle Mountain region of central Nepal (Fig. 1). The area also lies within the Chitwan-Annapurna Landscape (CHAL) which is rich in biodiversity, yet exposed to various anthropogenic disturbances associated with land use changes and infrastructure development. The study area features a wide topographic variation, from flat agricultural lands in river valleys dominated by intensive agricultural practices and settlement areas to rugged hilly areas dominated by agroforestry practices and intact forests. The region has a subtropical climate with a hot and dry summer, hot and humid monsoon season, and cold and dry winter. According to the climatic data recorded for 10 years (2011-2020 at Birenchowk station; 27°58'16" N, 84°35'21" E) in Gorkha district, the mean annual maximum temperature was 32°C in June and the mean annual minimum temperature was 8°C in January (Data obtained from the Department of Hydrology and Meteorology, Kathmandu on September 6, 2022). The mean annual precipitation over the same period was 1696 mm, with the highest monthly precipitation in July (423 mm) and the lowest in November (2 mm). The study region mainly has broadleaved forests such as the *Shorea robusta* forest, *Schima-Castanopsis* forest, and *Alnus nepalensis* forests.

The road network in the region includes highways,

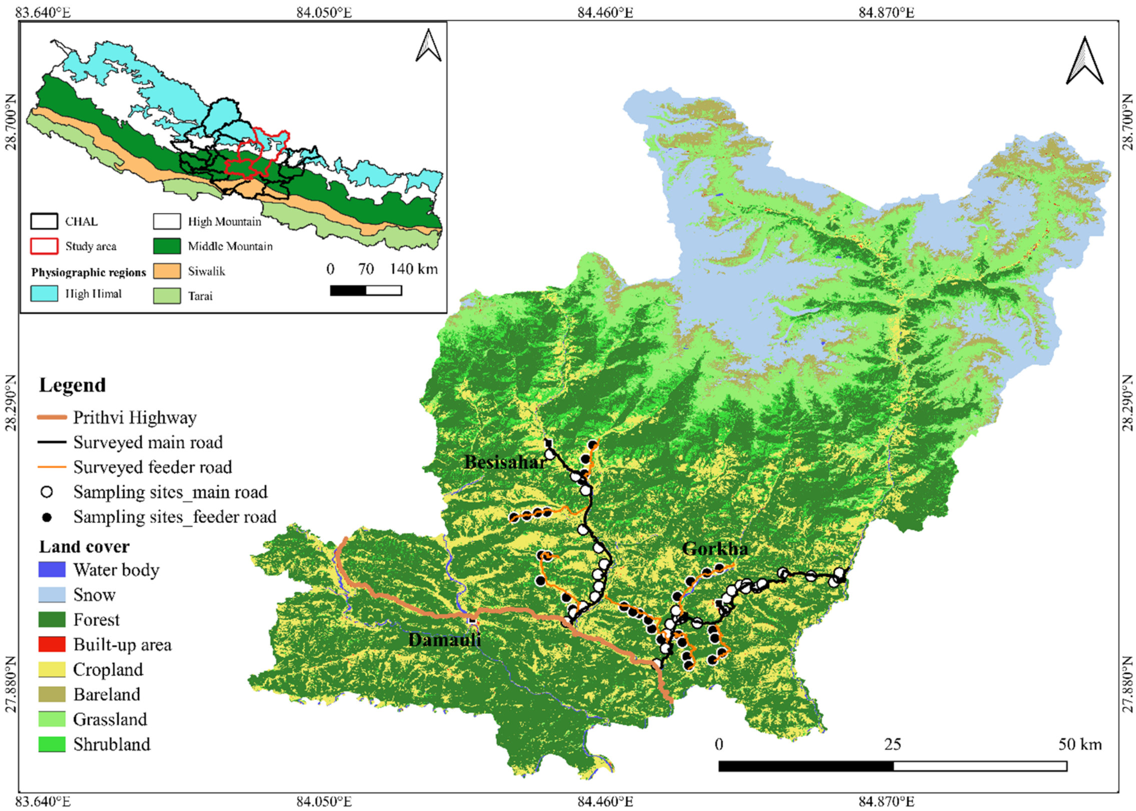

Fig. 1 Map of study area (Gorkha, Tanahun and Lamjung districts) showing main and feeder roads covered in the study along with sampling sites.

main roads, and feeder roads. In order to understand the impact of road types on IAPS distribution and abundance, we selected main (paved) and feeder roads (unpaved). The Prithvi highway, a major highway constructed over half a century ago, was excluded from our study because it mostly passes through market/residential areas and farmlands. The 'main roads' connect the Prithvi highway and district headquarters. The segment of main road that connects Gorkha district with the Prithvi highway was constructed more than four decades ago whereas other segments of the main road were constructed more than two decades ago. The 'feeder roads' connect rural areas to the main roads and were constructed in 5-10 years ago. We surveyed a total of 210 km of roads, including the main road (102 km) and feeder roads (108 km). A detailed list of surveyed main and feeder roads is available in Appendix 1.

2.2 Data collection

The field study was carried out from October 3–17, 2020. The sampling sites were located at an interval of 2.5±0.25 km along roads, depending upon the availability of appropriate sampling sites. We primarily focused forest area for sampling with some sites in shrublands and grasslands. The sites with steep slopes, settlement areas, and agricultural lands were excluded during sampling. At each sampling site, paired rectangular plots (25 m × 4 m; 100 m^2) were sampled: one adjacent to and along the road, and another 20 m away and parallel to it in the interior habitat (Appendix 2 for graphical illustration). Common disturbances along the road verges were generally absent in the interior habitats. The plots were further divided into five equal sub-plots (5 m × 4 m) for the convenient of field sampling. Occurrence of the IAPS and their cover were estimated in each plot, along with land use type and tree canopy cover. A checklist of 26 IAPS of Nepal reported by Shrestha (2019) was used as a reference for the IAPS. The IAPS cover and tree canopy were visually estimated using the Daubenmire cover class method in six cover classes i.e., 1 (0%-5%), 2 (5%-25%), 3 (25%-50%), 4 (50%-75%), 5 (75%-95%), and 6 (95%-100%) (Daubenmire 1959). Disturbances such as grazing/mowing/trampling, solid waste disposal, and soil exposure (debris/soil deposition/soil removal) were recorded on a scale of 0–3 (0: complete absence of disturbance; 1: up to 10% of the system affected; 2: 10%–50%; 3: >50%). The geographic coordinates (latitude, longitude, and elevation) were recorded using the Global Positioning System (Garmin eTrex 10). In total, 132 plots (66 along each road type) were sampled along main and feeder roads and their respective interior habitats.

2.3 Data analysis

Distribution map of individual IAPS were prepared with QGIS software (QGIS Development Team 2020) using geographic coordinates. Daubenmire cover classes were assigned with midpoint values (i.e., 2.5%, 15%, 37.5%, 62.5%, 85%, and 97.5%) (Daubenmire 1959), which were subsequently used to derive the cover of each IAPS on road verges and interior habitats, separately. We defined species richness as the number of IAPS enumerated in each plot (100 m^2). The mean and standard deviation of the IAPS cover and richness on road verges and interior plots were calculated. The frequency of all IAPS were calculated following Zobel et al. (1987). The richness and cover of IAPS were compared between road verges and interior habitats using a paired t-test to access the impact of roads in facilitating the spread of IAPS. On the other hand, the richness and cover of IAPS between two road types were compared using an independent sample t-test by merging the richness and averaging the cover of IAPS on road verges and interior habitats. We also compared environmental (e.g., tree canopy) and disturbance (e.g., grazing/mowing/trampling, exposed soil, solid waste disposal) variables between road verges and interior habitats using paired *t*-test. All these statistical analyses were performed using R statistical software (R Core Team 2020). Additionally, we assessed the similarity in IAPS composition between two road types (main and feeder roads) and between the road verges and interior habitats for each road type using the Jaccard Similarity Index (J). The index was calculated as $J = c/(a+b)$, where 'c' represents the number of species present in both habitats, while 'a' and 'b' denote the total number of species in the two different habitats (Zobel et al. 1987). The resulting value of J ranges from 0, indicating no shared species between the two habitats, to 1, indicating identical species composition in two habitats.

Ordination analysis was performed to analyze the association of IAPS occurrence with environmental variables (Data matrix available as Appendix 3). The IAPS cover was considered as a response variable, and other variables such as elevation, slope, tree canopy and disturbance were used as explanatory variables. Initially, de-trended correspondence analysis (DCA) was performed to find the variance in species data. Since the first axis of the DCA had a gradient length of 3.7 SD units (Appendix 4), being greater than 2.5 SD units and with an Eigen value > 0.5, the data was analyzed by direct gradient analysis i.e., canonical correspondence analysis (CCA) in R statistical software (R Core Team 2020).

3 Results

3.1 Diversity and distribution of IAPS

A total of 14 IAPS belonging to 12 genera and 6 families were recorded from the study area (Table 1), representing >50% of the 28 IAPS currently present in Nepal. More than half of the species (8 species) belongs to the family Asteraceae. All these species were either herb/climber or shrub, and native of new worlds (Americas). All but one of these species were reported first in Nepal between 1900 and 1970; the remaining species *Lantana camara* was reported before 1900 in Nepal. Out of 14 IAPS, *Chromolaena odorata*, *Mikania micrantha*, and *Lantana camara* are among 100 of the world's worst invasive alien species (*sensu* Lowe et al. 2000).

The IAPS showed a great spatial variation, and the species like *Ageratina adenophora, Ageratum houstonianum, Bidens pilosa, Chromolaena odorata, Mimosa pudica* and *Spermacoce alata* were widespread throughout the study area whereas the species like *Lantana camara, Mikania micrantha* and *Mesosphaerum suaveolens* were found only at few locations (Fig. 2, Appendix 5). The species with limited distribution (e.g., *Lantana camara, Mikania micrantha* and *Mesosphaerum suaveolens*) were found along main road but not along the feeder road. Similarly, *Parthenium hysterophorus* was also found

Table 1 List of invasive alien plant species, their habit, native distribution range, and first reported date in Nepal.

S.N.	Name of species	Common name	Family	Habit	Native distribution range*	First report in Nepal*	Elevation (m asl)	
							Nepal*	Study area
1	*Ageratina adenophora* (Spreng.) R. King & H. Rob.	Crofton weed	Asteraceae	Perennial subshrub	Central America (Mexico)	1952	130-3280	360-1310
2	*Ageratum conyzoides* L.	Billygoat	Asteraceae	Annual herb	Central and South America	1910	75-2140	360-760
3	*Ageratum houstonianum* Mill.	Blue billygoat Wee	Asteraceae	Annual herb	Mexico and Central America	1929	60-2160	315-1310
4	*Bidens pilosa* L.	Black-jack/Hairy beggar-tick	Asteraceae	Annual herb	Tropical America	1910	100-2930	315-1310
5	*Chromolaena odorata* (Spreng.) R. King & H. Rob.	Siam weed	Asteraceae	Shrub	Mexico, Central and South America	1956	75-1710	315-1310
6	*Lantana camara* L.	Lantana	Verbenaceae	Shrub	Central and South America	1848	70-1715	315-665
7	*Mesosphaerum suaveolens* (L.) Kuntze	Bushmint	Lamiaceae	Herb	Tropical America	1956	75-1065	430
8	*Mikania micrantha* Kunth	Mile-a-minute weed	Asteraceae	Perennial climber	Central and south America	1963	70-1200	445-840
9	*Mimosa pudica* L.	Sensitive plant	Fabaceae	Annual herb	Mexico to South America	1910	75-1495	315-1100
10	*Parthenium hysterophorus* L.	Parthenium	Asteraceae	Annual herb	South USA to South America	1967	60-1990	405-995
11	*Senna occidentalis* (L.) Link	Coffee Senna	Fabaceae	Perennial subshrub	Tropical America	1910	70-1405	430-795
12	*Senna tora* (L.) Roxb.	Sicklepod Senna	Fabaceae	Annual herb	South America	1910	75-1300	410-1095
13	*Spermacoce alata* Aubl.	Broadleaf Buttonweed	Rubiaceae	Perennial herb	West Indies and Tropical America	1967	110-2000	315-1310
14	*Xanthium strumarium* L.	Rough cockle-Bur	Asteraceae	Annual herb	America	1952	60-2500	425-530

*After Shrestha and Shrestha (2021)

mainly along the main road.

3.2 Frequency and cover of IAPS

In main road, frequency and cover of most species were higher on road verges than in the interior habitat. Along the main road, the frequency of *Ageratum houstonianum* was the highest along road verges (42%) as well as in the interior habitat (34%), followed by *Bidens pilosa* (road verges: 40%, interior habitat: 33%) (Table 2). Surprisingly, *Chromolaena odorata* had a slightly higher frequency (36%) in the interior habitat

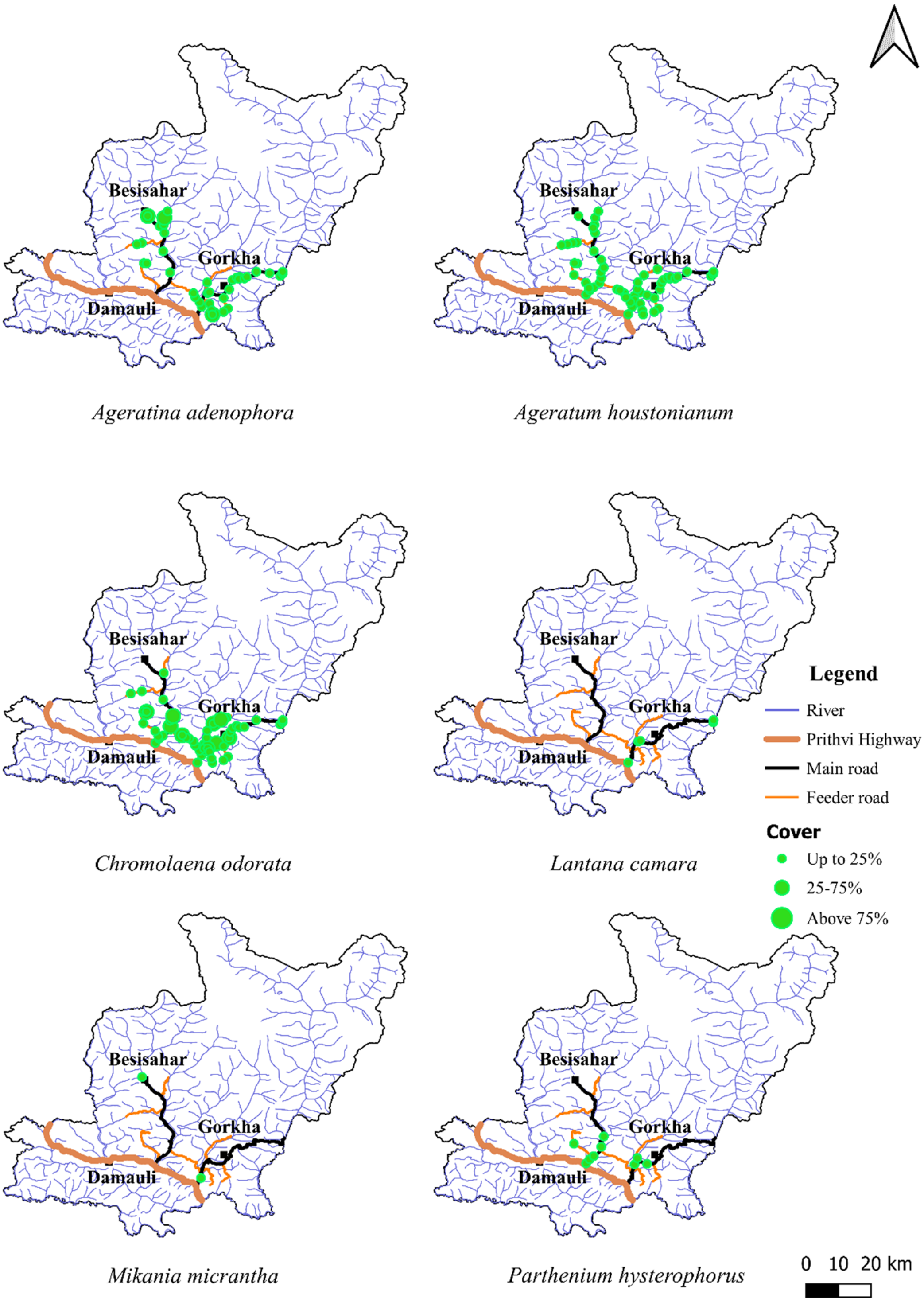

Fig. 2 Occurrence of six important invasive alien plant species recorded during the study. Place names refers to district headquarters. Occurrence of the remaining eight species have been presented in Appendix 5.

than on the road verges (33%). *Spermacoce alata* had the highest cover on the road verges (5%), followed by *Chromolaena odorata* (3.3%). But *Chromolaena odorata* had the highest cover in the interior habitat (3.6%), followed by *Spermacoce alata* (3.4%).

Along the feeder road, frequency and cover of all species were higher on the road verges than in the interior habitat (Table 2). Frequency of four species (*Ageratum houstonianum*, *Bidens pilosa*, *Chromolaena odorata* and *Spermacoce alata*) were nearly equal both on the road verges and in the interior habitat. Frequency of *Parthenium hysterophorus* and *Senna tora* were very low along the feeder road verges as well as in the interior habitat. *Chromolaena odorata* had the highest cover on the feeder road verges, followed by *S. alata*. On the contrary, *S. alata* had the highest cover in the interior habitat, followed by *C. odorata*. Cover of *P. hysterophorus, Senna occidentalis* and *S. tora* were very low.

3.3 Variation of IAPS richness, Cover and Species similarity

Along the main as well as the feeder road, the IAPS richness (#IAPS/100 m²) and the combined cover of all IAPS on road verges were significantly higher than in the interior habitats (Table 3). The difference was small for IAPS richness, but the cover on the road verges was 1.6 and 2 times higher than in the interior habitats of main and feeder road, respectively. When

Table 2 Frequency (%) and cover (%) of IAPS along the main and feeder roads in the study area.

Name of IAPS	Abbr. [a]	Frequency (%)				Cover (%)				Overall	
		Main road		Feeder road		Main road		Feeder road		Fre. (%)	Cover (%)
		Road verges	Interior	Road verges	Interior	Road verges	Interior	Road verges	Interior		
Ageratina adenophora	Age_aden	24.24	24.24	25.76	12.12	1.97	0.87	1.97	0.64	43.18	5.98
Ageratum conyzoides	Age_cony	9.09	3.03	0.00	0.00	0.12	0.03	0.00	0.00	6.06	0.15
Ageratum houstonianum	Age_hous	42.42	34.85	42.42	27.27	2.63	1.17	1.43	0.74	73.48	5.98
Bidens pilosa	Bid_pilo	40.91	33.33	42.42	27.27	1.97	0.66	2.15	0.59	71.97	5.37
Chromolaena odorata	Chr_odor	33.33	36.36	40.91	31.82	3.35	3.60	5.55	2.87	71.21	15.37
Lantana camara	Lan_cama	7.58	4.55	0.00	0.00	0.72	0.52	0.00	0.00	6.82	1.24
Mesosphaerum suaveolens	Mes_suav	0.0	1.52	0.00	0.00	0.00	0.40	0.00	0.00	0.76	0.40
Mimosa pudica	Mim_pudi	30.30	21.21	28.79	15.15	2.12	1.45	1.02	0.38	47.73	4.96
Parthenium hysterophorus	Par_hyst	10.61	3.03	3.03	1.52	0.59	0.02	0.06	0.01	9.09	0.67
Senna occidentalis	Sen_occi	3.03	0.00	3.03	3.03	0.08	0.00	0.02	0.02	4.55	0.11
Senna tora	Sen_tora	7.58	6.06	16.67	1.52	0.55	0.54	0.07	0.02	15.91	1.17
Spermacoce alata	Spe_alat	33.33	33.33	42.42	33.33	5.39	3.39	4.23	3.20	71.21	16.20
Xanthium strumarium	Xan_stru	10.61	9.09	7.58	1.52	0.67	0.24	0.42	0.04	14.39	1.37

[a] Used in Fig. 3. Abbr.=Abbreviation. Fre. = Frequency.

Table 3 IAPS richness (#IAPS/100 m²), and combined cover (%) of all IAPS in the main road (*n*=33) and feeder road (*n*=33) systems, both in road verge (*n*=33) and interior habitat (*n*=33).

Habitat type and statistical variables	IAPS richness (±SD)		IAPS cover (±SD)	
	Main road	Feeder road	Main road	Feeder road
Road verges	5.06 ± 1.69	4.85 ± 1.46	40.33 ± 16.49	33.83 ± 14.02
Interior	4.21 ± 1.85	3.09 ± 1.58	25.77 ± 21.07	16.98 ± 12.63
t-value	2.65	4.43	6.30	8.11
p-value	0.012	<0.001	<0.001	<0.001
Combined (Road verges + Interior)	5.91 ± 1.76	4.97 ± 1.51	33.05 ± 16.39	25.41 ± 11.93
t-value	2.33 [a]		2.17 [a]	
p-value	0.023 [a]		0.034 [a]	

[a] Based on comparison of the combined values between main road feeder road

two road types were considered, the IAPS richness and cover along the main road were significantly higher than the feeder road (Table 3). The difference was relatively small in species richness but the IAPS cover along the main road was 1.3 times higher than the feeder road. Despite small difference in species richness, the Jaccard Similarity Index (*J*) between road verges and interior habitats of both main (0.57) and feeder roads (0.61) was relatively low. The *J* value between main and feeder road was also low (0.49).

3.4 Factors influencing occurrence of IAPS

The de-trended correspondence analysis (DCA) explained nearly 57% of the variance in the data set of IAPS abundance (Appendix 4). There were 6 axes for constrained analysis, with a total inertia of 0.7419 and 20% variance, whereas unconstrained analysis consists of 12 axes, with a total inertia of 2.8686 and 79% variance (Appendix 6).

The CCA revealed that *Ageratina adenophora* (Age_aden) and *Spermacoce alata* (Spe_alat) were frequent at higher elevations (Fig. 3). On the other hand, *Chromolaena odorata* (Chr_odor), *Mesosphaerum suaveolens* (Mes_suav) and *Senna occidentalis* (Sen_occi) were found in habitats with disturbed soil and a low tree canopy. *Parthenium hysterophorus* (Par_hyst), *Mimosa pudica* (Mim_pudi) and *Ageratum conyzoides* (Age_cony) were frequently found in the degraded habitats at lower elevations with solid waste accumulation, however *Senna tora* (Sen_tora) was more frequent at habitats with grazing/mowing/trampling.

Table 4 Relative importance of environmental variables on explaining IAPS occurrence based on canonical correspondence analysis (CCA). The statistical significance (*p*-value) is obtained from permutation test.

Environmental variables explained	Variance	*F*-value	*p*-value
Elevation	0.24362	10.1914	0.001
Slope	0.07691	3.2174	0.002
Tree canopy	0.12452	5.2091	0.002
Grazing/mowing/trampling	0.09355	3.9135	0.001
Solid waste	0.08801	3.6818	0.017
Soil exposure	0.11528	4.8226	0.003

The CCA also revealed that the occurrence of the IAPS was affected by multiple environmental variables (Table 4). Among the environmental variables, elevation and disturbance (grazing/mowing/ trampling) appeared to have the strongest influence on the occurrence of the IAPS. The elevation explained 24% of the variance in species occurrence whereas the tree canopy explained 11% of the variance. Additionally, the road verges had lower tree canopy but higher solid waste disposal activities (along main road) and grazing/mowing/tramping (along main road) (Appendix 7).

4 Discussion

4.1 Diversity and spatial distribution

The study area constitutes the substantial number of invasive alien plant species (IAPS) (14 out of 28 total IAPS reported in Nepal) (Shrestha et al. 2021; Adhikari et al. 2022). A survey along road verges throughout central Nepal covering Tarai, Siwalik, Middle Mountain and High Mountain regions reported 18 species of invasive plants (Paudel 2015). That study covered the main roads included in the present study (Marsyangdi River-Gorkha and Dumre-Besisahar) and reported the invasion by 13 species. Hence, the occurrence of a high number of IAPS in relatively a small area suggests that the threats of plant invasions is very high in the Middle Mountain region of central Nepal. The spatial distribution patterns of 14 species in the study area showed that these IAPS might have invasion history of different length of time period. Species with longer invasion history are often widespread, invading most of their climatically suitable areas whereas the recent invaders are limited at a few locations (Pyšek and Jarošík 2005). Given that, the widespread species such as *Ageratina adenophora, Ageratum houstonianum, Bidens pilosa, Chromolaena odorata, Mimosa pudica* and *Spermacoce alata* might have a longer history of invasion. Other species such as *Lantana camara, Mikania micrantha* and *Mesosphaerum suaveolens* with their occurrence only at a few locations can be considered as the recent invaders in the study area. For example, *Mikania micrantha* appeared to be absent in the study area until 2013 (Poudel 2015) but in present study we found this species at two locations. The widespread species were found both along main and feeder road verges but the recent invaders were found primarily along the main road. This indicates that the new IAPS may first establish along main road verges, and subsequently spread into the feeder. For example, *L. camara*, *M. suaveolens* and *M. micrantha* are already widespread in other parts of Nepal (Adhikari et al. 2022), and the current study area is predicted climatically suitable for these species (Shrestha et al 2018). Additionally, infrastructure development, increased trade and tourism, urbanization, and global climate change have been identified as major drivers for the introduction and spread of IAPS in mountain environments (Pauchard et al. 2009; Gottfried et al. 2012). These factors can potentially facilitate further spread of the IAPS in the present study area. Therefore, in the absence of timely and appropriate control measures, there is a higher likelihood that recent invaders with currently limited distribution can become widespread in the near future.

We did not assess impacts of the IAPS but many of the species invading the present study area are well known for the negative ecological and economic impacts in the invaded regions of Nepal and other countries in Asia, Africa and Oceania. For example, *Chromolaena odorata, Lantana camara* and *Mikania micrantha* are among 100 of the globally worst invasive alien species (Lowe et al. 2000) and are known to have high ecological impacts in Nepal (Adhikari et al. 2022). Propagules (seeds and vegetative parts) of these species can disperse into a large area within a short period of time through natural agents (e.g., wind, bird) and anthropogenic activities. These species have also degraded prime habitats of the threatened wildlife species such as one-horn rhino (Murphy et al. 2013) and elephant (Wilson et al. 2013). Similarly, other species such as *Ageratina adenphora*, *Ageratum houstonianum* and *Parthenium hysterophorus* are reported to have significant ecological and socio-economic impacts in Nepal (Shrestha et al. 2015, 2019a).

4.2 Frequency and cover of IAPS across habitat types

The majority of IAPS were more frequent and abundant on the road verge of both types of roads than in the interior habitat, suggesting that the roads may potentially be serving as major dispersal corridors for IAPS. The higher frequency and abundance of IAPS on road verge than in the interior habitats were apparently linked to habitat quality, moderately stressful environments, and competitive exclusion, which might be the primary contributors to the establishment of road verge plant communities (Valladares et al. 2008). Road verge are human-created environments that differ from adjacent habitats in terms of drainage, light availability, and substrate character (Gordon et al. 2005). And, they provide a unique environment for weedy and invasive plant species to establish and spread (Gelbard and Belnap 2003; Pauchard and Alaback 2004; Flory and Clay 2006). The species that benefit from the road as a conduit for dispersal are frequently generalists. Their capacity to produce a large number of seeds, efficient seed dispersal mechanisms, and higher ability to thrive in a wide range of ecological conditions, such as those found along roads (Forman and Alexander 1998), frequently succeed in utilizing road verge to assist their persistence and spread across the environment. It is generally observed that IAPS seeds can be dispersed by vehicles, animals (Tewksbury et al. 2002; Haddad et al. 2003), or wind directed along a road (Liu et al. 1996), and roads serve as highly important dispersal pathways of IAPS in the landscape (Brothers 1992; Matlack 2002; Dark 2004; Essl 2005).

It is generally agreed that the characteristics of road networks, such as the type of road, traffic density, urbanization (distance to the urban center), and the nature and level of road management (such as maintenance cycles), have higher influence on the establishment of IAPS along road verge (Forman et al. 2003; Vakhlamova et al. 2016). Similarly, the availability of suitable ecological niches, changes in land-use patterns, and dispersal pathways all contribute to the spread of species at the landscape level (With 2002). On the other hand, plants with rapid growth, the ability to produce a large number of seeds (e.g. *Chromolana odorata, Lantana camara, Mikania micrantha*), and high adaptability (e.g. *Ageratina adenophora, Parthenium hysterophorus*) can spread quickly soon after the establishment of their founding populations on the road verges (Yang et al. 2019). For example, *M. micrantha*, mainly found in the southern lowland of Nepal, was not reported in the study area during a survey in 2015 (Paudel 2015), but we spotted founding populations of this noxious weed at two locations along main road verge in the present study. Hence, the expanding roads of the Middle Mountain region in Nepal may serve as important dispersal pathways for IAPS from the southern lowlands to the northern highlands. Eradication or containment of the founding populations of such invasive species can prevent their spread in to mountainous regions where IAPS management is more challenging than in lowland areas due to difficult topography and limited access (Pauchard et al. 2009). It is essential to prioritize regular monitoring of road verge vegetation for prediction, prevention, and early detection of potential IAPS. Effective risk assessment including the analysis of dispersal pathways offer a strategic framework for identifying potential IAPS and evaluating the impacts and potential threats in future (Venette et al. 2021). The outcomes of such risk assessment generally inform strategic management activities.

4.3 Impact of road types on the IAPS richness and combined cover

The main roads we surveyed, with potentially high traffic, had higher diversity and cover of the IAPS than along the feeder road as we expected. Several previous studies have also showed that the level of plant invasions depends on the intensity of road utilization (Tyser and Worley 1992; Forys et al. 2002; Gelbard and Harrison 2003; Pauchard et al. 2009; Dar et al. 2015). One potential factor that explains how roads promote the spread of alien plants is the phases of road development, which includes paved roads, graded unpaved roads, graded roads with surface improvements, and ungraded four-wheel-drive tracks (Parendes and Jones 2000). Additionally, the effects of this type of road development process follow a gradient of increasing traffic volumes, habitat destruction during construction, and the frequency of vehicle and road maintenance disturbances. We found that the IAPS cover along main roads were higher than those along feeder roads. In other words, the IAPS were more diverse and abundant along main roads than feeder roads in the study area. Moreover, low IAPS similarity between the main and feeder roads, as revealed by a low Jaccard Similarity Index (*J*), indicated a distinct difference in the level and extent of disturbances as well as environmental conditions between these two road types. The frequent disturbances, high propagule pressure of invasive plants, and high traffic density might have facilitated early establishment of the IAPS along main road verges (Joly et al. 2011). Thus, the establishment of IAPS along roads might be related to traffic volume and the locations from which the vehicles come. Main roads in the study area are connected to the Prithvi highway and are used for both passenger and cargo transportation over large distances, frequently passing through different climatic regions, allowing alien species to be introduced at their new locations (Taylor et al. 2012; Menuz and Kettenring 2012). In contrast, feeder roads connect villages and main roads and thus serve more regionally restricted traffic by transporting a small number of passengers and materials, yet contribute to the spread and establishment of various IAPS.

4.4 Factors influencing IAPS occurrence

The primary ordination axis explained over 57% of the variance in the IAPS cover, implying that a substantial portion of the variation in species composition is captured and represents significant ecological patterns (Hill and Gauch 1980). We found that IAPS abundance were significantly influenced by elevation, tree canopy, soil exposure, and grazing/mowing/trampling. A decline in the number of invasive plants with increasing elevation has been reported in Nepal Himalaya (Bhattarai et al. 2014) and other mountain regions (e.g., Alexander et al. 2011; Zhang et al. 2015). With all IAPS present in the study area being native of tropical and subtropical region of Americas, the low number of IAPS at higher elevation is as expected. One commonly observed IAPS at higher elevation in the study area as well as in other parts of Nepal is *Ageratina adenophora* which is one of the most widespread and highly problematic IAPS in Nepal (Shrestha et al. 2019a; Adhikari et al. 2022). Low tree canopy, and thus high exposure to direct sunlight, along road verges provide highly conducive environment for most of the invasive plants (Christen and Matlack 2009). However, contrary to our expectation, *Chromolaena odorata* cover was higher in the interior habitat (with relatively high tree canopy) than on the road verges. One possible reason for a low *C. odorata* cover on the road verges might be related to weeding activities. Although the study area currently lacks specific management strategies for controlling IAPS, whether imposed by government institutions or non-governmental organizations, the Department of Roads periodically undertakes weed clearance along the road verges, typically once or twice a year, as part of maintenance procedures (personal observations of AA), but weeds in the interior habitat remain intact. Due to larger growth form of *C. odorata* compared to co-occurring other IAPS (e.g., *Spermacoce alata*), this species is likely to be targeted and removed first, resulting in its' low cover. This assertion is also supported by the result of the CCA (Fig. 3) which showed a low occurrence of *C. odorata* at sites with high level of mowing. It appears that soil exposure also promoted plant invasions in the study area. Soil is exposed after vegetation removal mainly due to maintenance related activities. Such exposed soil surface is often colonized by ruderal species including IAPS. Similarly, the disturbance associated with livestock grazing and mowing also promote plant invasions with increasing abundance of non-palatable IAPS (Bock et al. 2007; Tozer et al. 2008). This might be the reason for higher probability of the occurrence of non-palatable IAPS such as *Senna tora* at sites with frequent grazing and mowing.

5 Conclusion

We recorded a total of 14 IAPS from the Middle Mountain areas in central Nepal along road verge and adjacent vegetation, with some species already widespread and others with limited distribution, suggesting their initial stage of invasion. Species in the early stage of invasions in the study area (e.g., *Lantana camara, Mikania micrantha*) are already widespread in other parts of Nepal. Prioritization of these and other similar species through risk assessments for eradication or containment can prevent them from being widespread and protect native species and ecosystems from their negative impacts in future. The results also suggests that both main and feeder roads have been facilitating establishment and spread of the IAPS. In particular, activities such as livestock grazing, mowing and maintenance works appeared to promote plant invasions along road verges. A similar role of the roads in promoting IAPS can be anticipated in other regions of the country and beyond. Therefore, plant invasions have to be seriously accounted during the environmental impact assessment of road construction projects and subsequent mitigation measures to minimize the environmental impacts of road. In the absence of proper control measures, the expanding roads in the Middle Mountain region of Nepal can serve as a major dispersal corridor of the IAPS from the Tarai region in the south to Mountain regions in the north where management of IAPS could be more challenging than in the lowlands. Therefore, we urge for the regular monitoring of road verge vegetation and implement management activities in order to eradicate or contain the founding populations of recent invaders and control of the widespread species for preventing their further spread and potential impacts on the mountain ecosystem. To support the policy process, additional studies covering large geographic areas and all physiographic regions (Tarai to the High Himal) are required. Robust experimental design are currently available (e.g., Haider et al. 2022), and the use of such common protocol in future studies enables researchers and policy makers to collate new data into a global database for better informing the policy and management decisions.

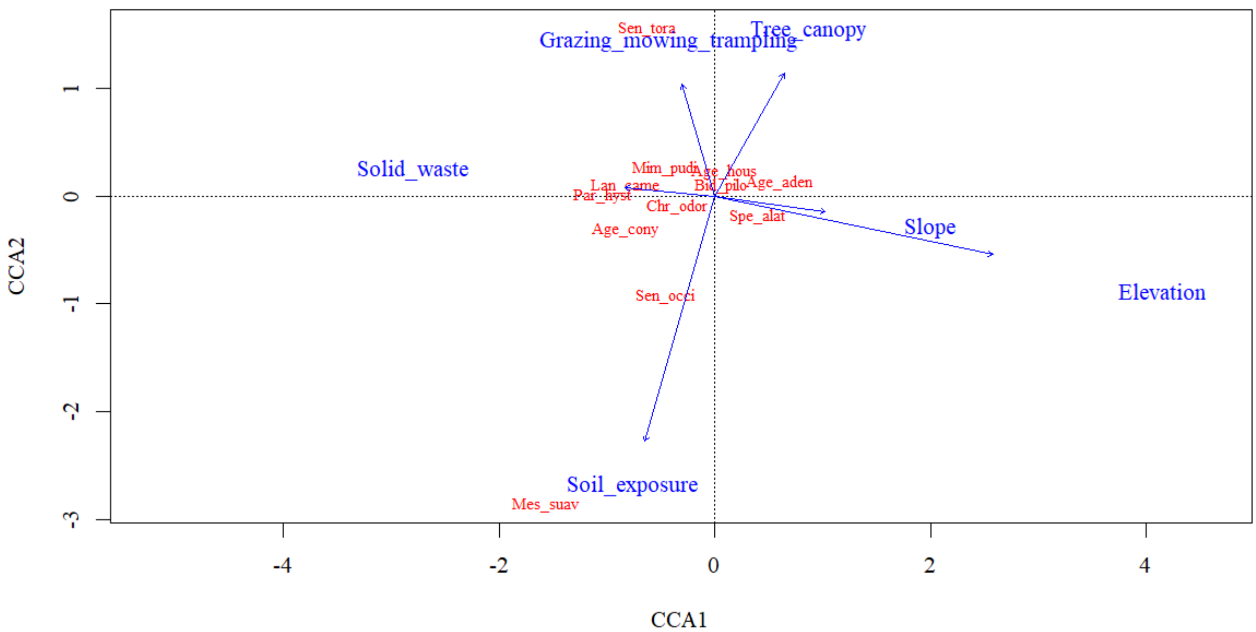

Fig. 3 Canonical correspondence analysis (CCA) plot showing the influence of environmental variables and disturbance factors on IAPS occurrence. For full name of the species, refer Table 2.

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Author Contributions

Ananda ADHIKARI: Investigation, Methodology, Data curation, Formal analysis, Visualization, Writing-original draft. Adarsha SUBEDI: Investigation, Methodology, Data curation. Achyut TIWARI: Supervision, Writing-review & editing. Bharat Babu SHRESTHA: Conceptualization, supervision, Writing-review & editing.

Ethics Declaration

Availability of Data/Materials: The datasets generated during this study is available as Appendices associated with this article.

Conflict of Interest: The authors declare no conflict of interest.

Electronic Supplementary Material:

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References

Adhikari B, Shrestha BB, Watson MF, et al. (2022) Invasive Alien Plants of Nepal: A Field Guide to 27 Problematic Species. Nepal Academy of Science and Technology, Lalitpur, Nepal.

Alexander JM, Kueffer C, Daehler CC, et al. (2011) Assembly of nonnative floras along elevational gradients explained by directional ecological filtering. Proc Natl Acad Sci USA 108: 656-661. https://doi.org/10.1073/PNAS.1013136108/SUPPL_FILE/PNAS.201013136SI.PDF

Ansong M, Pickering C (2013) Weed seeds on clothing: A global review. J Environ Manage 144:203-211. https://doi.org/10.1016/J.JENVMAN.2014.05.026

Bhattarai KR, Måren IE, Subedi SC (2014) Biodiversity and invasibility: Distribution patterns of invasive plant species in the Himalayas, Nepal. J Mt Sci 11:688-696. https://doi.org/10.1007/S11629-013-2821-3

Bock CE, Bock JH, Kennedy L, Jones ZF (2007) Spread of non-native grasses into grazed versus ungrazed desert grasslands. J Arid Environ 71:229-235. https://doi.org/10.1016/J.JARIDENV.2007.03.004

Brothers TS (1992) Postsettlement plant migrations in Northeastern North America. Am Midl Nat 128:82. https://doi.org/10.2307/2426414

Christen D, Matlack G (2009) The habitat and conduit functions of roads in the spread of three invasive plant species. Biol Invasions 11:453-465. https://doi.org/10.1007/S10530-008-9262-X

Coffin AW (2007) From roadkill to road ecology: A review of the ecological effects of roads. J Transp Geogr 15:396-406. https://doi.org/10.1016/J.JTRANGEO.2006.11.006

Dar PA, Reshi ZA, Shah M (2015) Roads act as corridors for the spread of alien plant species in the mountainous regions: A case study of Kashmir Valley, India. Trop Ecol 56:49-56.

Dark SJ (2004) The biogeography of invasive alien plants in California: an application of GIS and spatial regression analysis. Divers Distrib 10:1-9. https://doi.org/10.1111/J.1472-4642.2004.00054.X

Daubenmire RF (1959) Canopy coverage method of vegetation analysis. Northwest Sci 33:43-64.

Delgado JD, Arroyo NL, Arévalo JR, Fernández-Palacios JM (2007) Edge effects of roads on temperature, light, canopy cover, and canopy height in laurel and pine forests (Tenerife, Canary Islands). Landsc Urban Plan 81:328-340. https://doi.org/10.1016/J.LANDURBPLAN.2007.01.005

DoLIDAR (2016) Statistics of Local Road Network. Department of Local Infrastructure Development and Agricultural Roads (DoLIDAR), Ministry of Physical Infrastructure & Transport, Government of Nepal, Kathmandu.

Early R, Bradley BA, Dukes JS, et al. (2016) Global threats from invasive alien species in the twenty-first century and national response capacities. Nat Commun 7:1-9. https://doi.org/10.1038/ncomms12485

Essl F (2005) Invasion history and phytosociological affinities of Johnson grass (*Sorghum halepense*) - a case study from eastern Upper Austria. Tuexenia 25:251-268.

Flory SL, Clay K (2006) Invasive shrub distribution varies with distance to roads and stand age in eastern deciduous forests in Indiana, USA. Plant Ecol 184:131-141. https://doi.org/10.1007/S11258-005-9057-4/TABLES/1

Forman RTT, Alexander LE (1998) Roads and their major ecological effects. Annu Rev Ecol Syst 29:207-231. https://doi.org/10.1146/ANNUREV.ECOLSYS.29.1.207

Forman RTT, Reineking B, Hersperger AM (2002) Road traffic and nearby grassland bird patterns in a suburbanizing landscape. Environ Manage 29:782-800. https://doi.org/10.1007/s00267-001-0065-4

Forman RTT, Sperling D, Bissonette J, et al. (2003) Road Ecology: Science and Solutions. Island Press, Washington D.C.

Forys EA, Allen CR, Wojcik DP (2002) Influence of the proximity and amount of human development and roads on the occurrence of the red imported fire ant in the lower Florida Keys. Biol Conserv 108:27-33. https://doi.org/10.1016/S0006-3207(02)00086-1

Foxcroft LC, Spear D, van Wilgen NJ, McGeoch MA (2019) Assessing the association between pathways of alien plant invaders and their impacts in protected areas. NeoBiota 43:1-25. https://doi.org/10.3897/NEOBIOTA.43.29644

Gelbard JL, Belnap J (2003) Roads as conduits for exotic plant invasions in a semiarid landscape. Conserv Biol 17:420-432. https://doi.org/10.1046/J.1523-1739.2003.01408.X

Gelbard JL, Harrison S (2003) Roadless habitats as refuges for native grasslands: interactions with soil, aspect, and grazing. Ecol Appl 13:404-415.

Gordon D, Greenberg C, Crownover S, Slapcinsky J (2005) Effects of unpaved road soils on persistence of three non-native grass species. Nat Aeras J 25:257-262.

Gottfried M, Pauli H, Futschik A, et al (2012) Continent-wide

response of mountain vegetation to climate change. Nat Clim Chang 2:111-115.
https://doi.org/10.1038/nclimate1329
Haddad NM, Bowne DR, Cunningham A, et al. (2003) Corridor use by diverse taxa. Ecology 84:609-615.
Haider S, Kueffer C, Bruelheide H, et al. (2018) Mountain roads and non-native species modify elevational patterns of plant diversity. Glob Ecol Biogeogr 27:667-678.
https://doi.org/10.1111/GEB.12727
Haider S, Lembrechts JJ, McDougall K, et al. (2022) Think globally, measure locally: The MIREN standardized protocol for monitoring plant species distributions along elevation gradients. Ecol Evol 12:e8590.
https://doi.org/10.1002/ECE3.8590
Hallett SG (2006) Dislocation from coevolved relationships: a unifying theory for plant invasion and naturalization? Weed Sci 54:282-290.
https://doi.org/10.1614/WS-05-100R2.1
Hansen MJ, Clevenger AP (2005) The influence of disturbance and habitat on the presence of non-native plant species along transport corridors. Biol Conserv 125:249-259.
https://doi.org/10.1016/J.BIOCON.2005.03.024
Hill MO, Gauch HG (1980) Detrended correspondence analysis: An improved ordination technique. Vegetatio 42:47-58.
https://doi.org/10.1007/BF00048870/METRICS
Joly M, Bertrand P, Gbangou RY, et al. (2011) Paving the way for invasive species: road type and the spread of common ragweed (*Ambrosia artemisiifolia*). Environ Manag 48:514-522.
https://doi.org/10.1007/S00267-011-9711-7
Karmakar NC, Ballav J, Hazra A (2021) Roadside vegetation in and around the megacity of Kolkata along an urbanisation gradient. Acta Bot Hung 63:77-86.
https://doi.org/10.1556/034.63.2021.1-2.6
Laurance WF, Goosem M, Laurance SGW (2009) Impacts of roads and linear clearings on tropical forests. Trends Ecol Evol 24:659-669.
https://doi.org/10.1016/J.TREE.2009.06.009
Lázaro-Lobo A, Ervin GN (2019) A global examination on the differential impacts of roadsides on native vs. exotic and weedy plant species. Glob Ecol Conserv 17:e00555.
https://doi.org/10.1016/J.GECCO.2019.E00555
Lembrechts JJ, Milbau A, Nijs I (2014) Alien roadside species more easily invade alpine than lowland plant communities in a subarctic mountain ecosystem. PLoS One 9:e89664.
https://doi.org/10.1371/JOURNAL.PONE.0089664
Liu J, Chen JM, Black TA, Novak MD (1996) E-ε modelling of turbulent air flow downwind of a model forest edge. Boundary-Layer Meteorol 77:21-44.
https://doi.org/10.1007/BF00121857
Lowe S, Boudjelas S, Browne M, De Poorter M (2000) 100 of the world's worst invasive alien species : a selection from the Global Invasive Species Database. The Invasive Species Specialist Group (ISSG) a specialist group of the Species Survival Commission (SSC) of the World Conservation Union (IUCN), Auckland, New Zealand.
Matlack GR (2002) Exotic plant species in Mississippi, USA: critical issues in management and research. Nat Areas J 22:241-247.
McDougall KL, Alexander JM, Haider S, et al. (2011) Alien flora of mountains: global comparisons for the development of local preventive measures against plant invasions. Divers Distrib 17:103-111.
https://doi.org/10.1111/J.1472-4642.2010.00713.X
Menuz DR, Kettenring KM (2012) The importance of roads, nutrients, and climate for invasive plant establishment in riparian areas in the northwestern United States. Biol Invasions 15:1601-1612.
https://doi.org/10.1007/S10530-012-0395-6
Mittermeier RA, Turner WR, Larsen FW, et al. (2011) Global biodiversity conservation: the critical role of hotspots. In: Zachos F, Habel J (eds.), Biodiversity Hotspots. Springer, Berlin, Heidelberg. pp 3-22.
Mortensen DA, Rauschert ESJ, Nord AN, Jones BP (2009) Forest roads facilitate the spread of invasive plants. Invasive Plant Sci Manag 2:191-199.
https://doi.org/10.1614/IPSM-08-125.1
Murphy ST, Subedi N, Jnawali SR, et al. (2013) Invasive mikania in Chitwan National Park, Nepal: the threat to the greater one-horned rhinoceros *Rhinoceros unicornis* and factors driving the invasion. Oryx 47:361-368.
https://doi.org/10.1017/S003060531200124X
Paiaro V, Cabido M, Pucheta E (2011) Altitudinal distribution of native and alien plant species in roadside communities from central *Argentina*. Austral Ecol 36:176-184.
https://doi.org/10.1111/J.1442-9993.2010.02134.X
Paini DR, Sheppard AW, Cook DC, et al. (2016) Global threat to agriculture from invasive species. Proc Natl Acad Sci USA 113:7575-7579.
https://doi.org/10.1073/PNAS.1602205113/SUPPL_FILE/PNAS.1602205113.SAPP.PDF
Parendes LA, Jones JA (2000) Role of light availability and dispersal in exotic plant invasion along roads and streams in the H. J. Andrews Experimental Forest, Oregon. Conserv Biol 14:64-75.
https://doi.org/10.1046/J.1523-1739.2000.99089.X
Pauchard A, Alaback PB (2004) Influence of elevation, land use, and landscape context on patterns of alien plant invasions along roadsides in protected areas of South-Central Chile. Conserv Biol 18:238-248.
https://doi.org/10.1111/J.1523-1739.2004.00300.X
Pauchard A, Kueffer C, Dietz H, et al. (2009) Ain't no mountain high enough: plant invasions reaching new elevations. Front Ecol Environ 7:479-486.
https://doi.org/10.1890/080072
Paudel N (2015) Diversity and distribution of invasive alien plant species along road network in Central Nepal. M. Sc. Thesis. Central Department of Botany, Tribhuvan University, Kathmandu, Nepal.
Pyšek P, Jarošík V (2005) Residence time determines the distribution of alien plants. In: Inderjit (ed.), Invasive Plants: Ecological and Agricultural Aspects. Birkhäuser Basel. pp 77-96.
QGIS Development Team (2020) QGIS Geographic Information System. Open Source Geospatial Foundation.
https://qgis.org
R Core Team (2020) R: A language and environment for statistical computing. R Foundation for Statistical Computation, Vienna, Austria.
https://www.R-project.org/.
Rankin K, Sigdel T, Rai L, et al. (2017) Political economies and political rationalities of road building In Nepal. Stud Nepali Hist Soc 22:42-84.
Richardson DM, Pyšek P (2006) Plant invasions: merging the concepts of species invasiveness and community invasibility. Prog Phys Geogr 30:409-431.
https://doi.org/10.1191/0309133306PP490PR
Seipel T, Kueffer C, Rew LJ, et al. (2012) Processes at multiple scales affect richness and similarity of non-native plant species in mountains around the world. Glob Ecol Biogeogr 21:236-246.
https://doi.org/10.1111/J.1466-8238.2011.00664.X
Shrestha BB (2019) Management of invasive alien plants in Nepal: current practices and future prospects. In: Garkoti SC, van Bloem S, Fule PZ and Semwal RL (eds.), Tropical Ecosystems: Structure, Functions and Challenges in the Face of Global Change. Springer, Singapore. pp 45-68.
Shrestha BB, Pokhrel K, Paudel N, et al. (2019b) Distribution of *Parthenium hysterophorus* and one of its biological control agents (Coleoptera: *Zygogramma bicolorata*) in Nepal. Weed Res 59:467-478.
https://doi.org/10.1111/WRE.12384
Shrestha BB, Shabbir A, Adkins SW (2015) *Parthenium hysterophorus* in N epal: a review of its weed status and possibilities for management. Weed Res 55:132-144.

https://doi.org/10.1111/WRE.12133
Shrestha BB, Shrestha KK (2021) Invasions of alien plant species in Nepal: patterns and process. In: Pullaiah T, Ielmini MR (eds) Invasive Alien Species: Observations and Issues from Around the World. John Wiley & Sons Ltd. pp 168-183.
Shrestha BB, Shrestha UB, Sharma KP, et al. (2019a) Community perception and prioritization of invasive alien plants in Chitwan-Annapurna Landscape, Nepal. J Environ Manage 229:38-47. https://doi.org/10.1016/J.JENVMAN.2018.06.034
Shrestha HS, Adhikari B, Shrestha BB (2021) *Sphagneticola trilobata* (Asteraceae): first report of a naturalized plant species for Nepal. Rheedea 31:77-81. https://doi.org/10.22244/rheedea.2021.31.02.07
Shrestha UB, Sharma KP, Devkota A, et al. (2018) Potential impact of climate change on the distribution of six invasive alien plants in Nepal. Ecol Indic 95:99-107. https://doi.org/10.1016/J.ECOLIND.2018.07.009
Spellerberg IF (1998) Ecological effects of roads and traffic: a literature review. Glob Ecol Biogeogr Lett 7:317-333.
Sudmeier-Rieux K, McAdoo BG, Devkota S, et al. (2019) Mountain roads in Nepal at a new crossroads. Nat Hazards Earth Syst Sci 19:655-660. https://doi.org/10.5194/NHESS-19-655-2019
Taylor K, Brummer T, Taper ML, et al. (2012) Human-mediated long-distance dispersal: an empirical evaluation of seed dispersal by vehicles. Divers Distrib 18:942-951. https://doi.org/10.1111/J.1472-4642.2012.00926.X
Tewksbury JJ, Levey DJ, Haddad NM, et al. (2002) Corridors affect plants, animals, and their interactions in fragmented landscapes. Proc Natl Acad Sci 99:12923-12926. https://doi.org/10.1073/PNAS.202242699
Tozer KN, Chapman DF, Quigley PE, et al. (2008) Controlling invasive annual grasses in grazed pastures: population dynamics and critical gap sizes. J Appl Ecol 45:1152-1159. https://doi.org/10.3897/NEOBIOTA.41.26599
Trombulak SC, Frissell CA (2000) Review of ecological effects of roads on terrestrial and aquatic communities. Conserv Biol 14:18-30. https://doi.org/10.1046/J.1523-1739.2000.99084.X
Tyser RW, Worley CA (1992) Alien flora in grasslands adjacent to road and trail corridors in Glacier National Park, Montana (U.S.A.). Conserv Biol 6:253-262. https://doi.org/10.1046/J.1523-1739.1992.620253.X
Vakhlamova T, Rusterholz HP, Kamkin V, Baur B (2016) Recreational use of urban and suburban forests affects plant diversity in a Western Siberian city. Urban For Urban Green 17:92-103. https://doi.org/10.1016/J.UFUG.2016.03.009
Valladares F, Tena D, Matesanz S, et al. (2008) Functional traits and phylogeny: What is the main ecological process determining species assemblage in roadside plant communities? J Veg Sci 19:381-392. https://doi.org/10.3170/2008-8-18378
Venette RC, Gordon DR, Juzwik J, et al (2021) Early intervention strategies for invasive species management: connections between risk assessment, prevention efforts, eradication, and other rapid responses. In: Therese MP, Deborah MF, Deborah CH, et al. (eds.), Invasive Species in Forests and Rangelands of the United States: A Comprehensive Science Synthesis for the United States Forest Sector. Springer International Publishing, Cham, Switzerland. pp 111-131
Von Der Lippe M, Kowarik I (2007) Long-distance dispersal of plants by vehicles as a driver of plant invasions. Conserv Biol 21:986-996. https://doi.org/10.1111/J.1523-1739.2007.00722.X
Wilson G, Desai AA, Sim DA, Linklater WL (2013) The influence of the invasive weed *Lantana camara* on elephant habitat use in Mudumalai Tiger Reserve, southern India. J Trop Ecol 29:199-207. https://doi.org/10.1017/S0266467413000205
With KA (2002) The landscape ecology of invasive spread. Conserv Biol 16:1192-1203. https://doi.org/10.1046/J.1523-1739.2002.01064.X
Yang L, Huang H, Saeed M, et al. (2019) Anatomical study of seed and fruit morphology of an invasive weed buffalobur (*Solanum rostratum* Dunal). Pak J Bot 51:241-246. https://doi.org/10.30848/PJB2019-1(12)
Zhang W, Yin D, Huang D, et al. (2015) Altitudinal patterns illustrate the invasion mechanisms of alien plants in temperate mountain forests of northern China. For Ecol Manage 351:1-8. https://doi.org/10.1016/J.FORECO.2015.05.004
Zobel DB, Jha PK, Behan MJ, Yadav UKR (1987) A Practical Manual for Ecology. Ratna Book Distributors, Kathmandu.