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Conflicting edge influence on herbaceous species in open areas vs. underneath oak trees in forest fragments in Iran

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Abstract
Since the type of forest influences vegetation patterns from the edge-to-interior forest, site-specific edge studies are needed but there have been few studies in open-canopied forests such as oak savannahs. Our objective was to compare patterns of herbaceous plant diversity along the forest edge-to-interior gradient between open areas and underneath oak trees in the Zagros Forest in Iran. We established eighteen transects from the forest edge to the interior in small and large forest fragments to sample herbaceous species in five 0.25 m^2 quadrats at 1 m intervals from the base of the tree to the open area at different distances from the forest edge. We analyzed the data using randomization tests for edge influence and generalized linear mixed models. Edge influence had a positive effect on herbaceous species richness and diversity underneath oak trees but a negative effect in open areas. At forest edges, species richness and diversity significantly decreased from the tree base toward open areas, but exhibited the opposite pattern away from the edge. Edge influence extended up to 50 m from the forest edge to the interior. Our findings highlight the importance of considering forest type and stand heterogeneity when studying edge influence on plant diversity. Our results show that edge studies are needed for specific forest types, particularly in heterogeneous landscapes, to ensure appropriate conservation of species diversity. We recommend establishing a 50-m buffer zone along edges in the Zagros Forest in Iran to minimize negative edge influence on herbaceous plant diversity.

Keywords Distance of edge influence · Edge effects · Fragment size · Open canopy forest · Species richness · Zagros forests

Introduction

Destruction and degradation of natural ecosystems are the primary causes of the decrease in global biodiversity (Rands et al. 2010). Human disturbances such as logging, forest clearing for agriculture, and landscape fragmentation are related to loss of natural habitat and biological diversity (Barima et al. 2010). Fragmentation, the division of natural habitat into smaller and more isolated fragments (Haddad et al. 2015), alters forest dynamics, microclimate, and biological cycles, leading to an increase in invasive and pioneer species (Barima et al. 2010), and changes in environmental factors, community structure, and species composition close to the edge of fragments (Harper et al. 2005; Pardini et al. 2017).

One of the major consequences of forest fragmentation is an increase in area affected by forest edges (Honnay et al. 2002; Fahrig 2003). We define edge influence as the difference in biotic and abiotic factors at the forest edge relative to the interior forest (Harper et al. 2005). Edge influence can have important impacts on species diversity, and community and ecosystem functioning (Laurance et al. 2006; Willmer et al. 2022). Along a forest edge-to-interior gradient, species are exposed to changes in microclimatic conditions such as greater light availability, temperature variation, and wind exposure (Harper et al. 2005; Magnago et al. 2015; Erdős et al. 2018), which affect the establishment and development of plants (Coelho et al. 2016; Erdős et al. 2019; Wekesa et al. 2019; Da Costa et al. 2022). The edge is often dominated by light-demanding species with high growth and low

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survival rates (Magnago et al. 2015; Bragion et al. 2019). In contrast, the shady and humid conditions in the forest interior favor long-lived shade-tolerant species (Bragion et al. 2019), which grow slowly but are taller and larger, resulting in greater aboveground stand biomass (Da Silva et al. 2019). Edges also influence litter decomposition and nutrients, and subsequently alter species diversity and richness along the forest edge-to-interior gradient (Bennett and Saunders 2010).

Edge influence has been a principal topic of interest in studies of landscape processes associated with edge creation and fragmentation during the last few decades (Harper et al. 2005; Franklin et al. 2021). Forest herbaceous species can be influenced by the edge because their composition is affected by altered forest conditions such as increased light availability and reduced soil moisture (Pellissier et al. 2013). Furthermore, conditions at the forest edge have been found to be more heterogeneous compared to the interior (Ewers and Didham 2006). Previous studies have shown that forest edges influence woody plant species richness and diversity in different ecosystems including in South Africa (Ruwanza et al. 2018), Tanzania (Kacholi 2014) and Brazil (Fontoura et al. 2006; Sampaio and Scariot 2011). However, few studies have investigated the herbaceous layer diversity in response to created edges (Liepa et al. 2020). Studies show that plant species richness and diversity of understory species decreased from the forest edge-to-interior forest in central-southern China (Li et al. 2018) and in southwestern France (Alignier and Deconchat 2013). However, the opposite trend of higher species richness in the forest interior compared to edge has been found in northern France and Atlantic Forest in Brazil (Bergès et al. 2013; Mendes et al. 2016). No edge influence on species richness was reported in southwestern Amazon forests (Phillips et al. 2006).

Studies of edge influence on vegetation in open, dry forests are limited compared to more humid ecosystems. For instance, studies have been conducted in black spruce boreal forest in Canada (e.g., Harper et al. 2016) and tropical cerrado in Brazil (e.g., Dodonov et al. 2013), which are humid ecosystems. Moreover, no edge research has considered differences in edge influence on herbaceous vegetation in different habitats within a heterogeneous open-canopied forest or the interaction between edge influence (forest edge-to-interior gradient) and the gradient from the tree base to open area away from the tree canopy.

The Zagros Forest, an open-canopied temperate forest dominated by *Quercus* spp., is the largest forested land in Iran and has been fragmented by human activities such as fuelwood cutting, agriculture and livestock grazing. The forests have been significantly destroyed and their potential productivity has been lost due to social problems and inadequate management practices (Eshaghi Rad et al. 2018). In a previous study in this forest, we investigated edge influence on herbaceous plant species diversity and soil properties along the forest edge-to-interior gradient (Valadi et al. 2022). Here we investigate edge influence further by considering the effect of distance from the tree base into an open area on herbaceous species richness and diversity at different distances along the forest edge-to-interior gradient. Our first objective was to determine how herbaceous species richness and diversity varied along two gradients: (i) from the tree base to open area and (ii) from the forest edge to the interior, and to ascertain whether these two gradients interact. Our second objective was to assess the differences in small vs. large fragments. We tested the following null hypotheses: (i) species diversity is the same at different distances from the base of tree, (ii) changes in species diversity from the forest edge-to-interior are the same at different distances from the tree base toward open area, and (iii) patterns along gradients are the same in small and large forest fragments. By understanding the effects of edge influence on herbaceous species richness and diversity, forest managers could develop more effective strategies to conserve and protect these important ecosystems.

Material and methods

Study area

We conducted our research in the semi-arid Kermanshah province in Iran (34° 1′ 20.37″ N, 46° 23′ 54.93″ E, 1650 m asl). *Quercus brantti,* the main tree species in our study area, forms even-aged stands with a density of 70 individuals per ha and canopy cover < 50% (Jazirei and Ebrahimi Rastaghi 2003). Average annual precipitation and temperature were 489 mm and 21.4 °C, respectively. The lowest and highest monthly average temperatures were 8.2 °C in January and 35.2 °C in August 2019. From the past to present, these forests have been settled by residents and nomads resulting in deforestation in some parts and severe damages in others. Due to the lack of adequate conservation planning, this settlement created forest fragments of varying sizes.

Data collection

To investigate edge influence on species richness and diversity of herbaceous species in sparse oak forest, we selected three small (5–7 ha) and three large (13–18 ha) fragments on 20–25% north-facing slopes. We chose fragments with similar physiographical conditions to isolate the effect of edge influence and we maintained a distance of approximately 1 km between fragments. We established three transects from the edge to the forest interior in each of the three small and three large forest fragments for a total of 18 transects. The first transect in each fragment was randomly chosen (using random coordinates) and the other two transects were placed 200 m on either side parallel to the first one. Herbaceous vegetation was sampled in May and June 2019 at 0 (forest edge), 25, 50, 100, and 150 m distances (toward forest interior) along each transect (Mendes et al. 2016) for a total of 90 sampling points in the six forest fragments (15 per fragment, 45 in small and 45 in large fragments).

To understand how herbaceous vegetation richness and diversity change from the tree base to the adjacent open area we collected data on canopy cover. We measured the short and long crown diameters of all trees with a DBH greater than 7.5 cm in two quadrats (20 × 2 m) perpendicular to the main edge-to-interior transect at each sampling point. We collected herbaceous data in five 0.5 × 0.5 m (0.25 m^2) quadrats at 1 m intervals from the base of two trees at each sampling point (ten quadrats total). We selected the nearest tree on either side of the main transect and established the quadrats from the tree base towards open area and the main transect (Fig. 1). We recorded the number of individuals of all vascular herbaceous species < 0.5 m in height within each quadrat. Individuals were easily differentiated for most species, but we estimated the number of individuals for a few species with high density such as some grasses. Herbaceous species were identified to species level; nomenclature followed Ghahreman (1979–2003).

Data analysis

For each sampling point, we calculated the mean herbaceous species abundance for paired quadrats located at the same distance from the tree base for a total of five mean abundances (one for each distance from the tree base) for each species at each sampling point. Before data analysis, Shapiro–Wilk tests were used to test for data normality. Unless

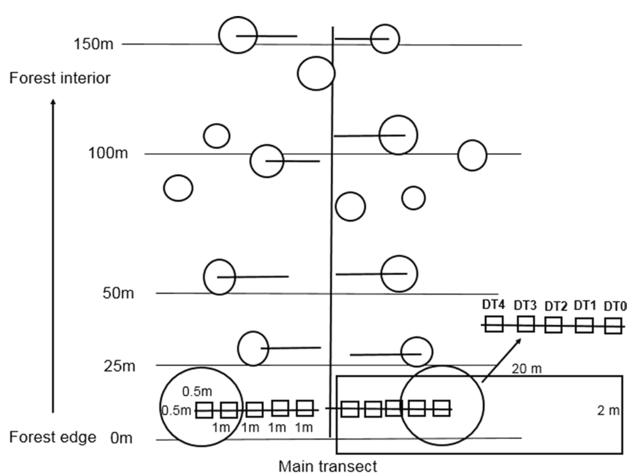

Fig. 1 Sampling design for the data collection. DT0 to DT4 refer to quadrat locations at 0 to 4 m from the tree base nearest to each sampling point along the main transect

otherwise indicated, all data analyses were conducted in R version 3.6.1 (R Core Team 2014) and SPSS 22 (Rovai et al. 2013).

Herbaceous layer diversity was quantified for each sampling point using three diversity indices: species richness (N = number of species), Shannon diversity as $H' = \sum_{i=1}^{s} p_i ln p_i$, where s equals the number of species and p_i is the relative cover of ith species (hereafter referred to as diversity) and evenness as $J' = H'/H'_{max}$ with $H'_{max} = \ln(S)$ (Magurran 2004). We analyzed diversity using the package “vegan,” version 2.5-6 (Oksanen et al. 2013). We calculated average canopy cover using CD = (C1 × C2) × π/4 where CD = canopy diameter, C1 = long diameter, C2 = short diameter (Zobeyri 2008) for each tree, which we then averaged for all sampling points for each transect. We detected significant differences in canopy cover between different distance from edge using the Tukey test in SPSS 22 (Rovai et al. 2013).

For each of the five distances from the tree base, we calculated the magnitude of edge influence (MEI) and distance of edge influence (DEI) (Harper and Macdonald 2011) for species richness, diversity and evenness. The MEI is a measure of the strength of edge influence, which we determined as MEI = $(X_d - X_i)/(X_d + X_i)$ where X_d = average of each variable at distance d from the edge, and X_i = average of each variable in interior forest (100 m and 150 m). This metric ranges from −1 (negative edge influence) to +1 (positive edge influence). We reported MEI at the distance from the edge where the absolute value of MEI was greatest for each variable. To calculate DEI for each variable, we used the randomization test of edge influence (RTEI) according to the methodology in Harper and Macdonald (2011). RTEI tests the significance of MEI for various distances from the edge compared to interior forest using randomization tests of the data. We reported DEI as either 0 m if MEI was significant only at 0 m or the set of two or more consecutive distances (or separated by one distance) where MEI was significant. Otherwise, DEI was reported as not significant and was excluded from average DEI. We calculated MEI and DEI separately for the five distances from the tree base into the open area.

We used generalized linear mixed models (GLMMs) (Magnago et al. 2017) to assess the effects and interactions of distance from forest edge, distance from tree base and fragment size on diversity indices. Distance from edge, distance from tree base and fragment size were fixed effects and fragment was a random effect. A Gaussian distribution was used for the normally distributed response variables. For analyzing GLMMs, we used the package “lme4” version 1.1-21 (Bates et al. 2014). Tukey tests were used to compare diversity indices at different distances from the edge for each distance from the tree base (Rovai et al. 2013). Indicator species analysis was applied to determine indicator species for different distances from the tree base in small and large fragments (Mccune and Mefford 2006). This method is based on relative fidelity and relative abundance of species and aims to identify species (Legendre and Legendre 2012).

Table 1 Average canopy area per tree (m^2) at different distances from the forest edge in small and large forest fragments

Distance (m)	Small fragments	Large fragments
0	9.52 ± 3.17^b	7.11 ± 0.74^b
25	12.00 ± 1.72^b	7.6 ± 0.74^b
50	11.60 ± 1.04^{ab}	9.40 ± 0.91^{ab}
100	18.07 ± 1.50^a	18.35 ± 3.97^a
150	14.40 ± 1.89^a	18.67 ± 3.65^a

Values at different distances within small or large fragments that share the same letter were not significantly different according to Tukey tests

Results

Trees had significantly larger canopies in the forest interior compared to the edge in both small and large fragments; canopy area per tree was particularly low within 50 m of the edges of large fragments (Table 1).

The results of the GLMM showed that distance from forest edge and distance from tree base significantly affected species richness, diversity and evenness (Table 2). Furthermore, the interaction between distance from edge and distance from tree base was significant. Fragment size was a significant factor in explaining species diversity and evenness, but not richness. The interactions of fragment size with distance from edge and with distance from tree base were significant except for the interaction between fragment size and distance from edge for species diversity, and the interaction between fragment size and distance from tree base for species diversity and evenness.

At the edges of small and large forest fragments (0, 25 m), species richness and diversity significantly

Table 2 Results of the generalized linear mixed models (GLMMs) showing the effects of distance from edge, distance from tree base and forest fragment size on species diversity indices

		Sum of squares	df	Mean square	F	Sig
Species richness	Intercept	28,960.22	1	28,960.22	5156.12	0.00
	Size	3.92	1	3.92	0.69	0.40
	Edge	921.71	4	230.43	41.02	0.00
	Tree base	625.33	4	158.83	28.27	0.00
	Size × Edge	126.45	4	31.62	5.63	0.01
	Size × Tree base	89.45	4	33.36	3.98	0.00
	Edge × Tree base	9689.69	16	586.79	104.48	0.00
	Size × Edge × Tree base	387.56	16	24.22	4.31	0.00
	Error	2246.67	400	5.62		
Shannon diversity	Intercept	1034.12	1	1034.12	7535.54	0.00
	Size	1.48	1	1.48	10.38	0.01
	Edge	11.64	4	2.91	20.45	0.00
	Tree base	4.98	4	1.24	8.74	0.00
	Size × Edge	1.07	4	0.27	1.87	0.11
	Size × Tree base	0.15	4	0.04	0.27	0.89
	Edge × Tree base	167.73	116	11.04	77.60	0.00
	Size × Edge × Tree base	10.56	16	0.66	4.64	0.00
	Error	56.94	400	0.14		
Evenness	Intercept	223.33	1	224.33	7882.87	0.00
	Size	0.65	1	0.65	18.61	0.00
	Edge	1.97	4	0.49	14.12	0.00
	Tree base	1.27	4	0.34	9.07	0.00
	Size × Edge	0.39	4	0.09	2.78	0.02
	Size × Tree base	0.26	4	0.06	1.86	0.11
	Edge × Tree base	8.39	116	0.52	15.01	0.00
	Size × Edge × Tree base	1.23	16	0.08	2.20	0.00
	Error	19.97	400	0.03		

edge = distance from edge, tree base = distance from base of tree decreased from the tree base (0, 1, 2 m) toward open area (3, 4 m) (Fig. 2). We found the opposite pattern in interior forest, with significantly higher species richness and diversity 3 and 4 m from the tree base. Evenness was significantly greater in the open area than at the base of trees at distances of 150 m from the edge in small fragments, and 100 m and 150 m from the edge in large fragments. The interaction between distance from tree base and distance from forest edge can also be viewed from a different perspective. Measures of species diversity at the tree base decreased from the forest edge to the interior but increased along the edge-to-interior gradient in open areas. Overall, diversity was lowest in open areas near the edge and next to tree bases in the forest interior, and greatest at tree bases at the edge and in open areas of interior forest.

The MEI was positive (greater values at the edge) for species richness, diversity and evenness for areas within 3 m of the tree base in both small and large fragments, but negative for distances greater than 3 m from the tree base in the open areas (Table 3). The DEI for species richness and diversity extended up to 50 m from the forest edge to the interior for nearly all distances from the tree base in both small and large forest fragments.

Indicator species were discernible only for the tree base (0, 1 m) at the forest edge (0 m) and in open areas (4 m from the tree base) at 100 and 150 m from the edge in small forest fragments (Table 4). For large fragments, indicator species were identified for comparable distances from the tree base and the forest edge, with the addition of the tree base (0, 1 m) at a distance of 25 m from the edge.

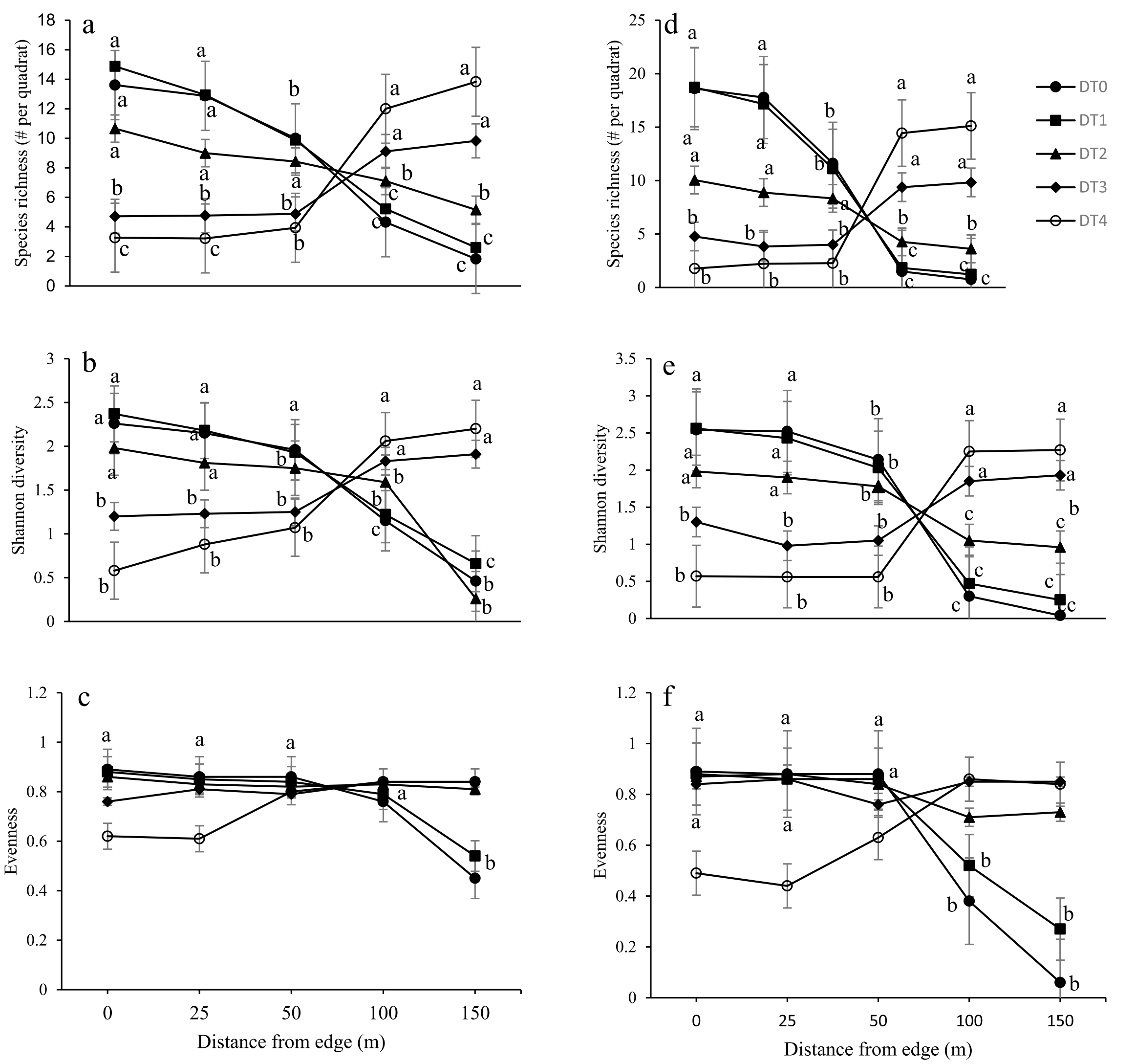

Fig. 2 Species richness, Shannon diversity and evenness at different distances from the forest edge and different distances from the tree base in small (**a**, **b**, **c**) and large (**d**, **e**, **f**) forest fragments. For a given distance from the tree base, values at different distances from the forest edge that share the same letter were not significantly different according to Tukey tests

Table 3 Magnitude (MEI) and distance of edge influence (DEI) of species diversity indices for different distances from the base of tree in small and large forest fragments

	Distance from tree base (m)	Small fragments		Large fragments	
		MEI	DEI (m)	MEI	DEI (m)
Species richness	0	0.6306	0–50	0.8980	0–50
	1	0.5834	0–50	0.8491	0–50
	2	0.2694	0–50	0.4365	0–50
	3	−0.3346	0–50	−0.4237	0–50
	4	−0.6006	0–50	−0.7852	0–50
Shannon diversity	0	0.4743	0–50	0.8708	0–50
	1	0.4306	0–50	0.7508	0–50
	2	0.1616	0–50	−0.0421	NA
	3	−0.2183	0–50	−0.2897	0–50
	4	−0.4311	0–50	−0.5989	0–50
Evenness	0	0.1893	0–50	0.1893	0–50
	1	0.1375	0–25	0.3731	0–50
	2	0.0239	NA	0.0938	0–50
	3	−0.476	NA	−0.1117	NA
	4	−0.1570	0–25	−0.2707	0–50

Discussion

Overall, we found opposing patterns of edge influence on herbaceous understory vegetation in oak savannah forest fragments in the Zargos Forest of Iran. Edge influence was positive for herbaceous species diversity at tree bases but negative in the open areas between trees. Stated another way, diversity was greatest under trees compared to open areas up to 50 m from the edge, but the opposite pattern occurred in the forest interior (100 and 150 m from the forest edge) with greater diversity in open areas. Micro-environmental variation along the forest edge-to-interior gradient might explain these opposing patterns; a different microclimate at the edge may favor a different plant community from that found in the interior (Noss and Cooperrider 1994). Documented changes in microclimate typical of forest edges include higher light, air and soil temperatures, wind speed, and vapor pressure, and lower relative humidity and soil moisture (Young and Mitchell 1994). Increased evaporation and reduced soil moisture adjacent to the forest edge are crucial drivers behind differences in forest vegetation between forest edge and interior (Herbst et al. 2007; Riutta et al. 2016). Soil carbon and moisture levels are higher in shaded areas than in open areas at the forest edge (Joshi et al. 2001). Combined with additional light penetration, these wetter conditions with more organic matter under the canopy at the forest edge likely favor more species, resulting in higher richness and diversity compared to the drier, nutrient-poor conditions in open areas. Greater herbaceous species richness under tree canopies near the forest edge is associated with more organic matter and soil moisture, wind protection, decreased daily oscillations of temperature, and lower evapotranspiration rates, air, and soil temperatures (Ishii et al. 2013; Valladares et al. 2016; Ren et al. 2022).

Edge influence did not affect herbaceous species richness and diversity after 50 m. In contrast to forest edges, interior forest had greater canopy cover, resulting in less light availability. Although soil moisture is generally important, light is probably the most limiting factor for understory species in temperate forests (Dormann et al. 2020). This lack of light is more important for the establishment of herbaceous species, as shade reduces herbaceous species richness (Gillet et al. 1999; Fikadu and Zewdu 2021). Light is a key resource for the growth and survival of herbaceous species (Tinya et al. 2009; Plue et al. 2013; Garg et al. 2022) and is likely the reason we observed more herbaceous species in open areas compared to tree bases in interior forests, which had less available light because of greater canopy cover.

Many studies found that light availability has a major impact on herbaceous species composition (e.g., De Frenne et al. 2015; Medvecká et al. 2018). Most herbaceous species in sparse oak forests, such as *Tortilis* sp., *Hordeum* sp., and *Heteranthelium* sp. in open areas within the forest interior, and *Astragalus* sp. and *Trifolium* at forest edges, which mainly belong to Poaceae and Fabaceae, are adapted to high light conditions and are not usually found in low light conditions beneath the canopy. Greater light availability in open-canopied forest tends to promote the establishment of generalist and light-demanding species (Alignier et al. 2014).

Distance from the forest edge and from the tree base were crucial factors in the open canopy oak forests, as we found opposite patterns of edge influence on herbaceous species diversity for the tree base vs. open areas. We believe that these results are related to increasing canopy cover from the forest edge-to-interior, which mediates harsh abiotic environmental conditions such as light availability, wind speed, air temperature, and humidity and reduced soil evaporation (Sagar et al. 2012; Ishii et al. 2013; Valladares et al. 2016). Whereas light availability is positively correlated with understory plant species richness in temperate forests (Dormann et al. 2020), this relationship is not consistent across all forests. Studies have found varying relationships between light availability and plant species richness (Adler et al. 2011; Bartels and Chen 2010; Fuxai et al. 2014; Tinya and Ódor 2016). These relationships often depend on factors such as dominant tree species, stand density, soil properties, successional stage, and management (Härdtle et al. 2003; Fuxai et al. 2014). Carefully controlled grazing can increase plant diversity (Kirk et al. 2019); a study of Zagros forests showed that herbaceous and woody communities responded differently to various levels of grazing intensity (Ahmadi et al. 2022). In our study fragments were surrounded by

Table 4 List of herbaceous indicator species at different distances from the tree base and forest edge in small and large forest fragments

Large fragments			Small fragments		
Distance from edge (m)	Distance from tree base (m)	Species	Distance from edge (m)	Distance from tree base (m)	Species
0	0	*Gladiolus atroviolaceus* Boiss	0	0	*Alyssum marginatum* Steud.ex Boiss
0	0	*Coronilla varia* L	0	0	*Lallemantia iberica* (M.Beib.) Fisch. & C.A.Mey
0	0	*Velezia rigida* L	0	0	*Euphorbia bupleuroides* Diels
0	0	*Minuartia hamata* (Hausskn.) Mattf	0	0	*Aegilops triuncialis* L
0	0	*Campanula cecilli* Rech.f. & Schiman	0	0	*Hordeum glaucum* Steud
0	0	*Salvia multicaulis* Vahl	0	0	*Euphorbia macroclada* Boiss
0	0	*Arenaria serpyllifolia* L	0	0	*Cephalaria syriaca* (L.) Schrad. ex Roem. & Schult
0	1	*Achillea aleppica* DC	0	1	*Ornithogalum brachystachys* K.Koch
0	1	*Eryngium thyrsoideum* Boiss	0	1	*Trifolium dasyurum* C. Presl
0	1	*Aegilops triuncialis* L	0	1	*Filago arvensis* L
0	1	*Alyssum marginatum* Steud. ex Boiss	0	1	*Teucrium scordium* L
0	1	*Tragopogon longrostris* Bisch	100	4	*Phlomis lanceolata* Boiss. & Hohen
0	1	*Lophochloa phleoides* (Vill.) Rchb	100	4	*Tortilis leptophylla* L
0	1	*Hordeum bulbosum*L	100	4	*Heteranthelium piliferum* (Banks & Soland)
0	1	*Bromus danthoniae* Trin	100	4	*Quercus brantii* Lindl
25	0	*phlomis persica* Benth	100	4	*Lamium amplexicaule* L
25	1	*Euphorbia inderiensis* Less. ex Kar. & Kir	150	4	*Rosularia elymatica* (Boiss. & Hausskn. ex Boiss
25	1	*Astragalus cyclophyllon* Beck	150	4	*Erodium cicutarium* (L.) Lher
25	1	*Trifolium scabrum* L	150	4	*Hordeum bulbosum* L
50	0	*Vulpia myuros* (L.) C.C.Gmel	150	4	*Echinaria capitate* (L.) Desf

Large fragments		
Distance from edge	Distance from tree base	Species
100	4	*Poa bulbosa* L
100	4	*Euphorbia macroclada* Boiss
100	4	*Muscari neglectum* Guss. ex Ten
100	4	*Euphorbia cheiradenia* Boiss
100	4	*Marrubium astracanicum* Jacq
100	4	*Senecio vernalis*Waldst. & Kit
150	4	*Fritillaria imperialis* L
150	4	*Quercus brantii* Lindl
150	4	*Atractylis cancellata* L
150	4	*Lamium amplexicaule* L
150	4	*Daphne mucronata* Royle
150	4	*Tortilis leptophylla* L
150	4	*Hordeum glaucum* Steud
150	4	*Heteranthelium piliferum* (Banks & Soland)
150	4	*Ziziphora capitata* L

agricultural land in which cattle grazing was prohibited by landowners.

Our result of a DEI of 50 m for herbaceous species richness and diversity agrees with other studies that indicate that DEI usually extends up to 50 m in temperate forests (Honnay et al. 2002) and 40 m in boreal forests (Harper and Macdonald 2001). Based on a synthesis by Franklin et al. (2021), average DEI for forest fragments surrounded by anthropogenic disturbances extends up to 42 m into the interior. Guirado et al. (2006) observed greater DEI (100 m) in oak and pine Mediterranean forests in Spain, indicating that DEI depends on various conditions in different ecosystems. Forest practices can strongly modify understory environmental conditions such as light, temperature, and soil moisture as well as species diversity (Ash and Barkham 1976; Grayson et al. 2012). In the Zagros Forest in Iran, considering that DEI extended up to 50 m for both under trees and in open areas, we recommend a 50 m buffer to conserve the interior herbaceous communities of these oak fragments. Further research on the impact of edge influence and buffer zones is urgently required in these fragmented forests to develop comprehensive management plans for each forest.

In conclusion, our study showed that forest edges influence herbaceous species richness and diversity and have different impacts on species at the tree base compared to in open areas in open-canopied oak forests of Iran. Efforts to conserve and restore forests and herbaceous plants should be integrated with sustainable forest management practices to maintain and enhance the ecosystem services of these forests, ensuring their benefits for present and future generations. Regional and national assessments are needed to determine where and what kind of conservation and restoration should occur to protect the remaining natural herbaceous plants. Our study has major implications for edge research beyond open oak forests in that we showed how edge influence on plant diversity can differ dramatically at a fine scale within the same ecosystem, even having opposite effects within a few meters from the tree base.

Author contributions All authors contributed to the study conception and design. Data collection and analysis were performed by GV, JER, YK and KAH. The first draft of the manuscript was written by GV and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Data availability Data will be made available on request.

Declarations

Conflict of interest The authors have no relevant financial or nonfinancial interests to disclose.

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