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Research Article

Edge influence on herbaceous plant species, diversity and soil properties in sparse oak forest fragments in Iran

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Abstract

Forest edges have been well studied in temperate and tropical forests, but less so in open canopy forests. We investigated edge influence on plant species diversity and soil properties in sparse oak forest fragments. Data were collected along three transects from the edge to the interior of three small (under 10 ha) and three large (over 10 ha) oak forest fragments in Kermanshah Province, Iran. We measured herbaceous plants (<0.5 m in height) and soil attributes at 0 (forest edge), 25, 50, 100 and 150 m. We quantified species diversity using the Shannon index, used rarefaction to compare species richness between two different sizes of fragments and applied non-metric multidimensional scaling ordination to investigate the variation in species composition. We estimated the distance of edge influence using randomization tests. Generalized linear mixed models with post-hoc Tukey's HSD tests were used to assess the effects of distance from edge and fragment size on diversity and soil properties. We found greater species richness, diversity and evenness at the edge of both small and large fragments and lower nitrogen and organic carbon at the edge compared to the interior of large fragments, with most changes within 50 m of the edge. Species composition, organic carbon and total nitrogen were significantly different between small and large fragments. Our findings of significant edge influence on herbaceous plants and soil properties in these sparse forests provide a significant contribution to the literature on edges, especially in relation to herbaceous plants.

Keywords edge influence, Zagros forest, large fragments, *Quercus brantii*, small fragments

伊朗稀疏橡木林片段对草本植物物种多样性和土壤特性的边缘影响

摘要：温带和热带森林中的森林边缘现象已经得到了很好的研究，但在稀疏的橡木林片段中的相关研究却较为缺乏。本文研究了稀疏橡木林片段对植物物种多样性和土壤特性的边缘影响。本研究沿着伊朗克尔曼沙赫省3个小型(<10 ha)和3个大型(>10 ha)橡木林片段的3个横断面收集了从边缘到内部的相关数据，测量了0(森林边缘)、25、50、100和150 m处的草本植物(高度<0.5 m)和土壤特性。使用香农指数量化了物种多样性，使用稀疏标准化方法比较了两个大小不同片段中的物种丰富度，并应用了非度量多维测度排序研究了物种组成的变化。通过随机化测试估算了边缘影响的距离，并利用Tukey

HSD事后检验法的广义线性混合模型评估了距边缘距离和片段大小对多样性和土壤特性的影响。研究结果表明，大小片段边缘具有较高的物种丰富度、多样性和均匀度，而大片段边缘的土壤氮和有机碳含量则较内部更低(边缘50 m范围内的变化最大)。大小片段的物种组成、土壤有机碳和氮总量都存在显著差异。本研究关于这些稀疏森林对草本植物和土壤特性产生显著边缘影响的发现，对于边缘研究，尤其是边缘和草本植物的相关研究具有重大贡献。

关键词：边缘影响，扎格罗斯森林，大片段，栎属植物(*Quercus brantii*)，小片段

INTRODUCTION

Forest fragmentation by human activities such as roads, agriculture and logging is recognized as a principal cause of biodiversity loss (Robinson and Sherry 2012). Direct and indirect effects on vegetation may modify forest structure and characteristics in the remaining fragments and increase the vulnerability of species that inhabit forest ecosystems by reducing suitable habitat and increasing isolation (Haddad *et al.* 2015). One of the most evident changes to a fragmented landscape is the creation of new edges. We define forest edge influence (hereafter referred to as edge influence) as the difference in biotic and abiotic factors at the border of the forest relative to the interior environment (*sensu* Harper *et al.* 2005), which may lead to changes in plant community composition or the environment as a function of distance from edge. Edge influence has been documented for changes in microclimate such as light, humidity, ground and air temperature, wind speed and soil properties at the forest edge compared to the forest interior (e.g. Arroyo-Rodríguez *et al.* 2017; Magnago *et al.* 2017; Ruwanza 2019). Edges also affect biological litter decomposition and nutrients and subsequently alter species diversity along forest edge-to-interior gradients (Bennett and Saunders 2010).

Although several factors contribute to edge influence (Laurance *et al.* 2006), fragment size is of particular importance because of a significant correlation between fragment size and distance from edge (Fletcher *et al.* 2007). The size of a forest fragment markedly affects ecological processes occurring therein; changes created by habitat edges are more prevalent in smaller fragments, which have a higher proportion of edge habitat than larger fragments (Mullu 2016). Positive (Fahrig 2013; Ma *et al.* 2015; Mullu 2016), neutral (Koszelnik-Leszek *et al.* 2015; Rajamurugan *et al.* 2017) and negative effects (Ribeiro *et al.* 2019) of fragment size on woody species richness and soil properties have been reported. However, the effect of fragment size on herbaceous species is still not clear.

Previous studies have provided different estimates of distance of edge influence (DEI, i.e. the distance from the forest edge up to which the value of a variable is significantly different from interior forest on species composition) (Franklin *et al.* 2021). Estimates of DEI vary depending on the forest ecosystem including up to 20 m in boreal (Harper *et al.* 2015), 16–137 m in temperate (Harper *et al.* 2005), 85–335 m in tropical (Laurance *et al.* 1998), 0–100 m in subtropical broadleaf (Kacholi 2014) and more than 175–225 m in African savanna (Muchiru *et al.* 2009) forests. However, studies on vegetation at edges are still lacking in many ecosystems, particularly in Africa and the Middle-East (Franklin *et al.* 2021). More research is needed to provide estimates of DEI to help forest conservation efforts in these regions.

Iran is one such region with few, if any, published studies on vegetation at edges. Zagros forest, dominated by *Quercus* spp., is the largest forested land in Iran but has been fragmented by human activities such as fuelwood cutting, clear-cutting for agriculture and livestock grazing (Eshaghi Rad *et al.* 2018). Oak forests in the Zagros region have an open canopy and may show different patterns of edge influence compared to dense forests. Other studies on vegetation at edges of open canopy forests have been conducted in very different ecosystems such as black spruce boreal forest in Canada (e.g. Harper *et al.* 2016) and Brazilian cerrado (e.g. Dodonov *et al.* 2019). We aimed to study the pattern of the responses of herbaceous species richness, diversity and evenness, and soil nitrogen, moisture, phosphorus, pH, organic carbon and potassium at edges of small and large fragments of oak forests in Zagros, Iran. Our objectives were to estimate DEI on these response variables and to analyze the effect of fragment size by comparing DEI and species composition between small and large fragments. We hypothesized that herbaceous species diversity and soil properties would increase along the edge-to-interior forest gradient and that soil properties and herbaceous species diversity would increase while the size of oak forest fragments increases.

MATERIALS 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 a.s.l.; Fig. 1a and b). 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. The predominant soil type belongs to the Entisol order developed on calcareous substrate (Jazireiy and Ebrahimi Rastaghi 2013).

Quercus brantii, the main tree species in our study area, formed even-aged forests with a stand density of 70 individuals per ha and canopy cover <50% (Jazireiy and Ebrahimi Rastaghi 2013). Secondary

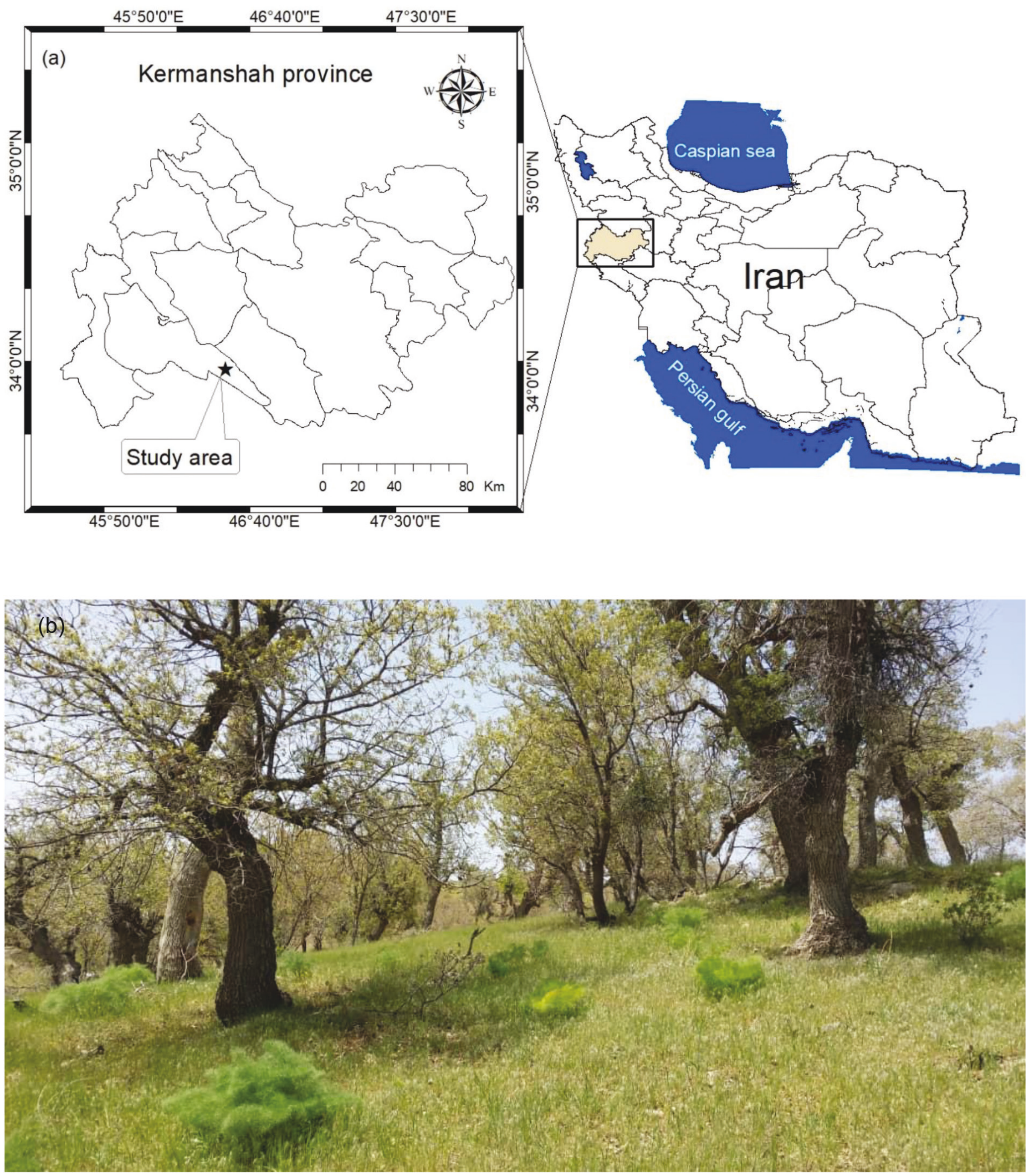

Figure 1: (**a**) Location of the study area. (**b**) Sparse oak forest of Iran.

species in these forests included *Cerasus microcarpa*, *Cratagus azarolus* and *Amygdalus lycioides* (Jazireiy and Ebrahimi Rastaghi 2013). These forests have been settled by residents and nomads resulting in deforestation in some parts and severe damages in others. Due to these problems and lack of proper and comprehensive management for conservation, human activities have created various fragments of different sizes. We selected three small (under 10 ha ranging from 5 to 7 ha) and three large (over 10 ha ranging from 13 to 18 ha) fragments on 20%–25% north-facing slopes in the region. We chose fragments with similar physiographical conditions to isolate the effect of edge influence and maintained a distance of about 1 km between fragments.

Data collection

In order to investigate the effect of distance from edge on herbaceous species diversity and soil properties of oak fragments, we established three transects from the edge to the forest interior in each of the three small and three large fragments. The first transect in each fragment was randomly located and the other two transects were located 200 m on either side of the first one. Measurements of vegetation and soil variables were collected in May and June 2019 at 0 (forest edge), 25, 50, 100, 150 m along each transect (Mendes *et al.* 2016) for a total of 90 sampling points in 6 forest fragments (15 per fragment; 45 in small and 45 in large fragments). We recorded herbaceous data in ten 0.5 m × 0.5 m (0.25 m^2) quadrats at each sampling point arranged at 1 m intervals on opposite sides of the nearest tree to each point orthogonal to the main transect (i.e. from the base of the tree toward open space) (Fig. 2). We recorded all vascular herbaceous species <0.5 m in height and counted the number of individuals of each species within each quadrat. Individuals were easily differentiated for most species, but for a few species with high density such as some grasses, we estimated the number of individuals for each species using a counting scale: 1–3, 4–10, 11–30, 31–60, 61–100, 101–150, 151–200 and 201–500 (Elzinga *et al.* 1998). Herbaceous species were identified to species level; nomenclature followed by Ghahraman (2001).

We collected a soil sample at each sampling point from the topsoil mineral layer (0–30 cm). Soil moisture (%), soil pH (soil reaction), total nitrogen (%), available phosphorous (mg/kg) and potassium (mg/kg) were determined by the gravimetric method, pH meter, the Kjeldahl method (Bremner

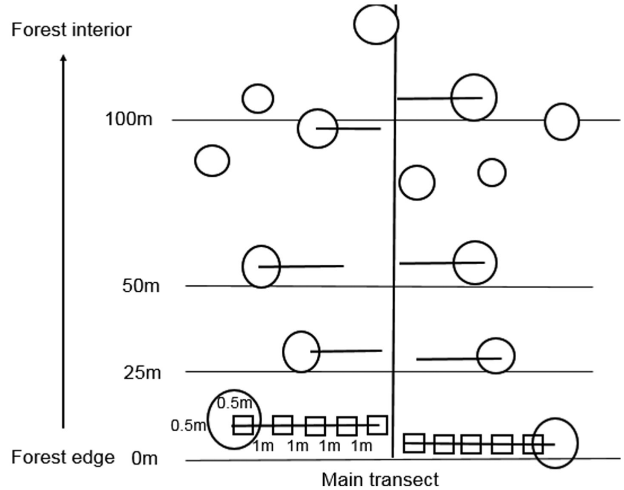

Figure 2: Schematic picture of the sampling design of one transect in one fragment. Trees are represented by circles and each sampling point is indicated by the second transect; quadrats are represented by squares. The diagram is not to scale.

1960), the Olsen method (Olsen 1954) and the flame photometric method (Piper 1944), respectively. Organic carbon (%) was measured following Walkley and Black (1934).

Data analysis

Abundance for each herbaceous species was calculated at each sampling point as the average density in the 10 quadrants. Before analysis, Shapiro–Wilk tests were used to test for data normality. Herbaceous layer diversity was quantified at each sampling point using three diversity indices: species richness (N = number of species), Shannon diversity as $H^t = \sum_{i=1}^{s} p_i \ln p_i$, 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.* 2012) in R version 3.6.1 (R Core Team 2014). To compare species richness between the two different sizes of fragments, we used rarefaction, which provides an estimation of expected species richness by taking account of different sampling efforts in different forest fragments (Magurran 2004). In order to compare different fragments, they must be standardized to a common number of individuals, which is shown in rarefaction curves.

We calculated the magnitude of edge influence (MEI) and DEI for all variables including: species richness, diversity and evenness and soil properties including total nitrogen, soil moisture, phosphorus, pH, organic carbon and potassium. 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 the interior (100 and 150 m) of the forest fragment (Harper *et al.* 2005). This metric ranges from −1 (negative edge influence) to +1 (positive edge influence). We reported MEI at the distance where the absolute value of MEI was greatest for each variable; MEI at other distances was used to determine DEI. To calculate DEI for each variable, we used the randomization test of edge influence (RTEI) with R version 3.6.1 (R Core Team 2014) according to Harper *et al.* (2011). RTEI tests the significance of MEI for various distances from the edge using randomization tests by comparing the data at a specific distance from the edge with the data in interior forest. We reported DEI as either 0 m (the closest distance to the edge) if MEI was significant only at that distance 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 applied non-metric multidimensional scaling ordination (NMDS) based on Bray–Curtis dissimilarity index to investigate the variation in species composition in the small and large fragments. In addition, multi-response permutation procedure (MRPP) was used to test the significant difference in species composition between small and large fragments. PC-ORD version 5.0 was used to analyze NMDS and MRPP (McCune and Mefford 1999). For the ecological interpretation of the ordination results, we computed Pearson correlation coefficients between sampling point scores on the first two axes and soil properties.

In order to assess the effect of distance from edge and fragment size and interactions between them on diversity indices and soil properties, we used generalized linear mixed models (GLMM) (Magnago *et al.* 2017). Distance from the edge and fragment size was taken as fixed effects and each fragment was considered as a random effect. A Gaussian distribution was used for the normally distributed response variables. For analyzing GLMM the package "lme4" version 1.1-21 (Bates *et al.* 2014) was used in R version 3.6.1 (R Core Team 2014). As there were significant interactions between fragment size and distance to edge on diversity indices and soil properties, Tukey's HSD tests were used to compare soil properties and diversity indices at different distances from the edge. For analyzing soil variables and diversity indices at the same distance from the edge in small *vs.* large fragments, we conducted *t*-independent tests using SPSS version 22 (Rovai *et al.* 2013).

RESULTS

We sampled 94 herbaceous species in the large fragments and 55 herbaceous species in the small fragments. Herbaceous species exhibited different responses to edge influence in small and large fragments (see Supplementary Table S1 for full floristic results). Some species were more frequent at the edge compared to the interior of small fragments whereas others were more abundant at the edges of large fragments (Table 1). Based on rarefaction curves that show the relationship between herbaceous richness and the number of individuals, large forest fragments had higher species richness than small forest fragments (Fig. 3). Species richness, diversity and evenness were all significantly higher at 0 m in small fragments compared to other distances; in large fragments, species richness and diversity were significantly higher at 0 and 25 m from the forest edge (Fig. 4). All diversity indices were higher in large fragments compared to small fragments only near the forest edge at 0 m and also at 25 m (Fig. 4a–c). In terms of soil properties, nitrogen and organic carbon had significantly lower levels at 0 m compared to the interior (100 and 150 m) in large fragments (Fig. 5a and e). Phosphorus levels were significantly higher at the forest edge (0 and 25 m) compared to the interior (100 m) in small fragments only (Fig. 5c). There was no significant variation along the forest edge-to-interior gradient for nitrogen, soil moisture, pH, organic carbon and potassium in small fragments or for soil moisture, phosphorus, pH and potassium in large fragments (Fig. 5). Some soil variables had significantly higher levels in large fragments compared to small fragments: organic carbon and nitrogen at 25 m (Fig. 5a and e), soil moisture at 50 m (Fig. 5b), phosphorus at 100 m (Fig. 5c), pH at 50 and 100 m (Fig. 5d) and potassium at 150 m (Fig. 5f).

Edge influence was positive (positive MEI, greater values at the forest edge) for soil moisture, phosphorus and potassium and was negative for nitrogen, pH and organic carbon in small fragments (Table 2; Supplementary Table S2). In large fragments, MEI was positive for phosphorus and potassium and negative for nitrogen, soil moisture, pH and organic carbon. MEI was positive

Table 1: Frequency (% of quadrats) of the most abundant herbaceous species at different distances (m) from the edge in small and large fragments

Species	Distance from the edge (m)									
	Small fragments					Large fragments				
	0	25	50	100	150	0	25	50	100	150
Aegilops triuncialis L.	44	44	0	0	0	56	56	22	0	0
Acanthophylum caespitosum Boiss	0	0	0	0	0	0	0	0	56	56
Acinos graveolens (M.B) Link	0	0	0	11	22	44	11	0	11	11
Alcea sulphurea (Boiss & Hohen.) Alef	0	0	0	0	0	44	22	0	0	0
Allium tuberosum Rottler ex Spreng	0	0	0	0	0	0	0	0	22	44
Alyssum marginatum Steud. ex Boiss	56	56	0	0	0	56	22	0	11	22
Astragalus cyclophyllon Beck	0	0	0	0	0	33	44	0	0	0
Astragalus aduncus Willd.	11	0	0	0	0	0	0	0	0	0
Atractylis cancellata L.	0	0	0	0	0	0	0	0	44	44
Campanula cecilli Rech.f. & Schiman	0	0	0	0	0	56	33	0	0	0
Callipeltis cucularis (L.) DC.	22	0	0	0	0	0	0	0	0	0
Coronilla varia L.	0	0	0	0	0	56	56	0	0	0
Cousinia concinna Boiss. & hausskn	0	0	0	0	0	44	44	0	0	0
Echinops tenuisectus Rech.f.	0	0	0	0	0	44	44	0	0	0
Euphorbia cheiradenia Boiss	0	0	0	0	0	0	0	0	44	33
Euphorbia szovitsii fisch. & C.A.Mey	0	0	0	0	0	0	0	11	22	22
Euphorbia falcata L.	33	11	0	0	0	0	0	0	0	0
Euphorbia macroclada Boiss	44	0	0	0	0	11	0	22	67	78
Fritillaria imperialis L.	0	0	0	0	0	0	0	0	11	44
Galium aparine L.	22	0	0	0	0	67	89	22	56	44
Gladiolus atroviolaceus Boiss	11	11	0	22	0	67	56	0	0	0
Lallemantia iberica (M.Beib.) Fisch. & C.A.Mey	44	0	0	0	0	0	0	0	11	11
Marrubium astracanicum Jacq.	0	0	0	0	0	0	0	0	33	22
Matricaria sp.	0	0	0	0	0	0	0	0	22	22
Muscari neglectum Guss. ex Ten.	0	0	0	11	22	0	0	0	67	67
Rosularia elymatica (Boiss. & Hausskn. ex Boiss.)	11	22	0	0	33	0	0	0	22	22
Salvia compressa L.	11	0	0	0	0	33	33	0	0	0
Stipa arabica Trin. & Rupr.	11	0	0	0	0	0	0	11	0	0
Tortilis leptophylla L.	100	100	100	100	100	100	100	100	100	100
Tragopogon longrostris Bisch.	100	100	89	100	100	100	89	78	22	33

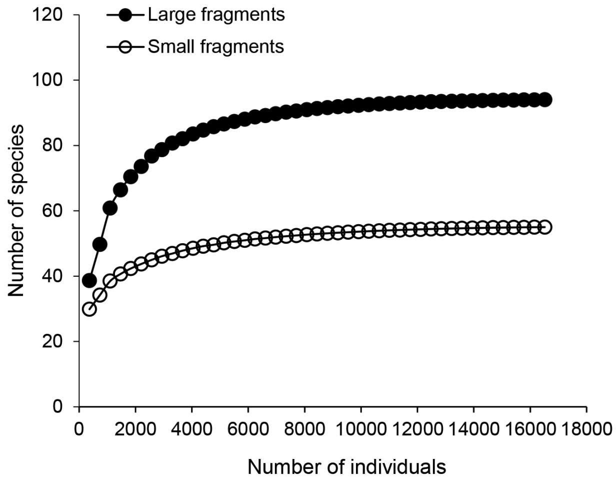

Figure 3: Rarefaction curves relating to herbaceous species in small and large fragments.

for all three diversity indices for both small and large fragments. The DEI of soil variables extended up to 25 m (except for pH) in small fragments and up to 50 m (except for phosphorus) in large fragments. The DEI of all diversity indices extended up to 50 and 25 m, respectively, in small and large fragments.

The results of the GLMM showed a significant interaction between fragment size and distance to forest edge for species richness, diversity and all soil variables except pH and soil moisture (Table 3; Supplementary Table S3). Distance from the forest edge had a significant effect on all soil variables except pH and soil moisture. Fragment size was significant for organic carbon, nitrogen and pH. Distance from the forest edge and fragment size significantly affected species richness, diversity and evenness ($P < 0.001$).

The NMDS ordination diagram of herbaceous species separated samples in the small and large fragments based on species composition (stress value = 0.171, Fig. 6). Based on the results of the MRPP, the difference of species composition between small and large fragments was significant (chance corrected within-group agreement (A) = 0.124, test statistic (T) = −32.67, $P < 0.001$). Correlations between soil variables and the NMDS axes showed that higher levels of organic carbon and nitrogen were associated with large fragments (positively correlated with the first axis and negatively correlated with the second axis, Table 4). Other correlations were not significant but the ordination diagram showed that higher pH was associated with small fragments.

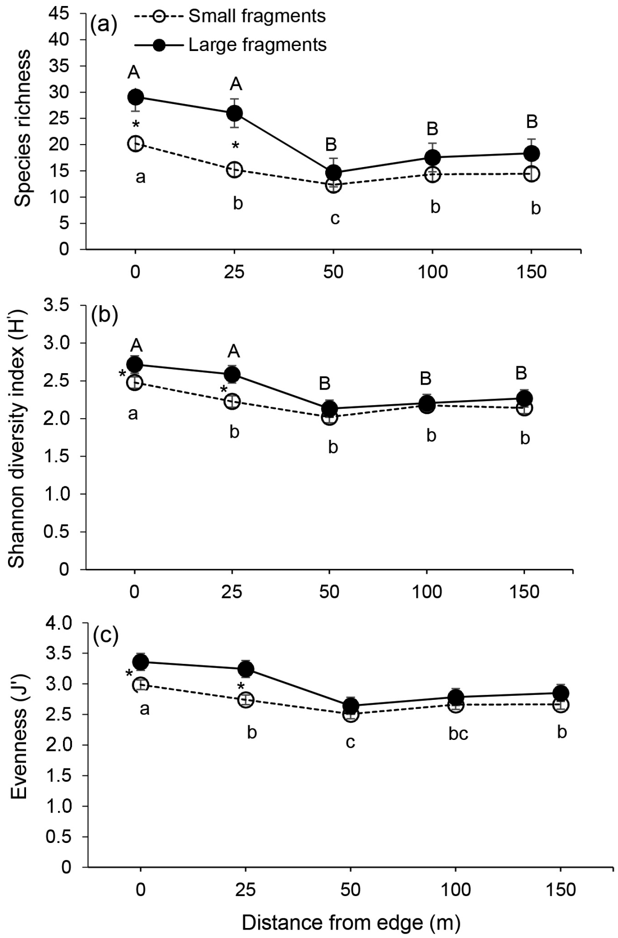

Figure 4: Mean and SE of species richness (**a**) diversity (**b**) and evenness (**c**) at different distances from the edge in large (filled circles with solid line) and small (open circles with dashed line) fragments. Values of a variable at different distances within the same size fragments that do not share the same letter are significantly different at $P = 0.05$. Values with no significant differences (ns) do not have any letter. Values in large fragments are shown with uppercase letters and values in small fragments are shown with lowercase letters. Significance was based on Tukey's HSD test. Results of *t*-independent tests indicating significantly different values between small and large fragments at a specific distance are shown by *.

DISCUSSION

Fragmentation of oak forests in landscapes dominated by deforestation and human settlement had a significant effect on herbaceous species composition, species diversity and soil properties in Iran through edge influence and fragment size. Fragment size affected the amount of organic carbon and total nitrogen in open canopy oak forests. Large fragments supported greater rates of plant production per unit area compared to small fragments; higher plant species richness promotes greater soil carbon and

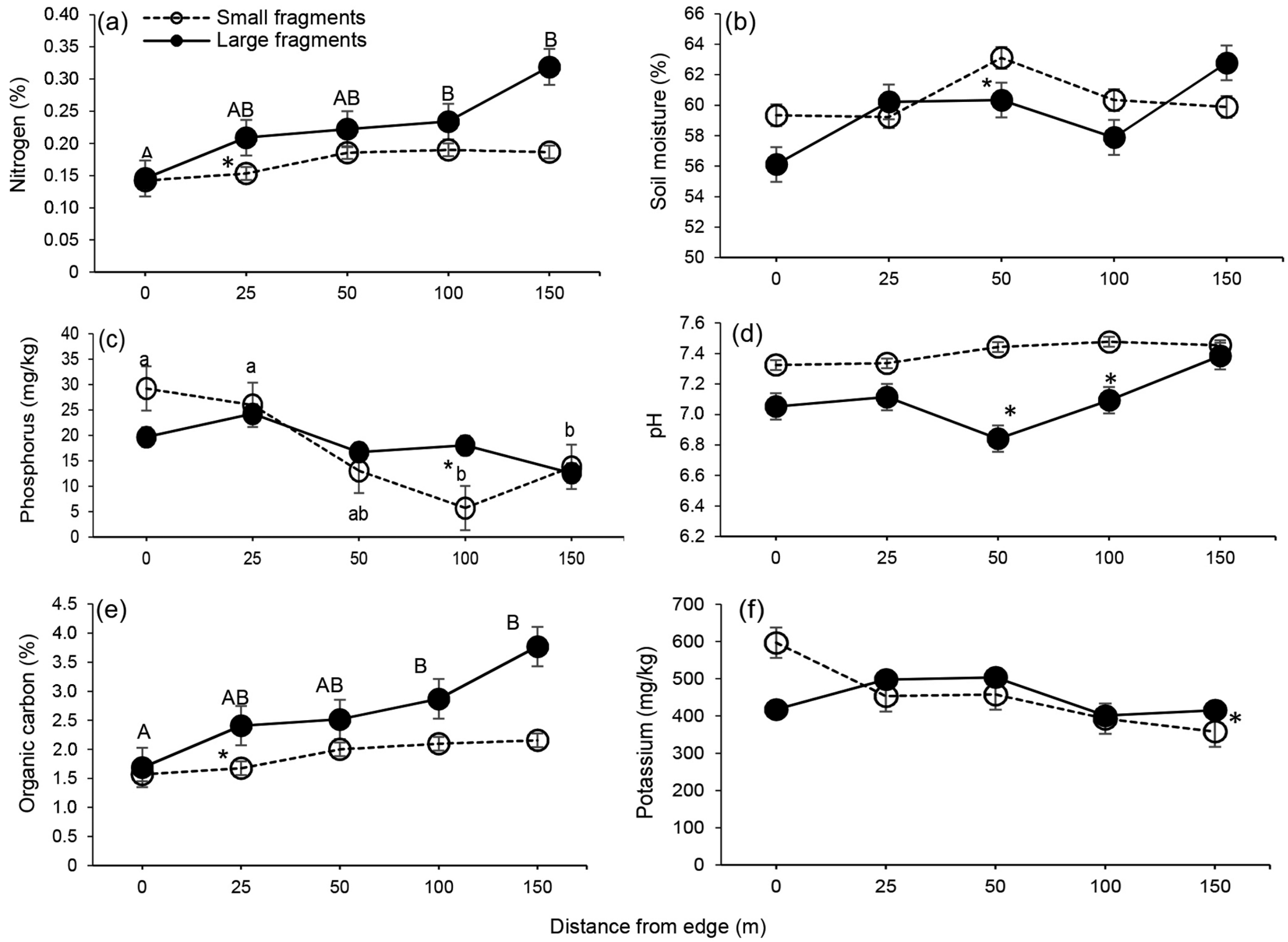

Figure 5: Mean and SE of soil variables: nitrogen (**a**), soil moisture (**b**), phosphorous (**c**), pH (**d**), organic carbon (**e**) and potassium (**f**) at different distances from the edge in large (filled circles with solid line) and small (open circles with dashed line) fragments. Values of a variable at different distances within the same size fragments that do not share the same letter are significantly different at $P = 0.05$. Values with no significant differences (ns) do not have any letter. Values in large fragments are shown with uppercase letters and values in small fragments are shown with lowercase letters. Significance was based on Tukey's HSD test. Results of *t*-independent tests indicating significantly different values between small and large fragments at a specific distance are shown by *.

nitrogen (Cong *et al.* 2014). Forest fragment size can influence the quality (C:N ratio and N) and quantity of organic matter; both of these parameters were higher in large fragments in deciduous forests in Kansas, USA (Billings and Gaydess 2008). However, it was reported that forest fragment size had no direct effect on changes in soil properties in pine forests of central Finland (Rantalainen *et al.* 2008). These contradictory results might be due to differences in vegetation type, stand density and anthropogenic intensity (Santana *et al.* 2021). These studies focused on tree layer diversity indicating that the patterns found for the arboreal layer were different from those that we found for the herbaceous layer.

Despite positive MEI for some soil variables (soil moisture, phosphorus and potassium) and negative MEI for the rest of the soil variables in small fragments, DEI only extended to 25 m and there were no significant differences in any of the soil variables except phosphorus between different distances from the forest edge. In smaller forest fragments, edaphic variables may not have shown a response with distance from the forest edge because they are dominated by forest edge (Bunyan *et al.* 2012). Different patterns across the forest edge were more pronounced for soil variables with DEI extending to 50 m in large fragments. Similar to our study, organic carbon also significantly increased from forest edges to interior in southern China (Shen *et al.* 2019). Greater soil fertility and nutrients have been found at the edges of forest fragments in Atlantic and Amazonian forests (Brazil) (Laurance *et al.* 2006; Ribeiro *et al.* 2019). These contradictory results might be due to the importance of light availability on the understory in dense forests of those studies (Brenes-Arguedas *et al.* 2011). Greater light and higher species richness are often found at forest edges, which promote greater soil carbon and nitrogen (Cong *et al.* 2014). Overall, DEI for soil variables in sparse oak forest of up to 50 m in our study is in the range found by other studies (25–180 m) (Honnay *et al.* 2002).

Edges influenced herbaceous species richness, diversity and evenness in open canopy oak forests. Furthermore, species composition was significantly influenced by fragment size with greater herbaceous species richness, diversity and evenness in larger fragments. A lower proportion of larger fragments is affected by edge influence resulting in more species (Rogan and Lacher 2018). As fragment size decreases, fragments become more dominated by forest edges; therefore, forest edges affect smaller fragments more intensively (Bunyan *et al.* 2012). This pattern was also found for natural fragments (Santana *et al.* 2021). The effect of fragment size on diversity varies based on the type of vegetation. Most studies on the effects of fragment size on tree species richness and diversity have found positive effects (Fahrig 2013; Ma *et al.* 2015; Mullu 2016) or neutral effects (Koszelnik-Leszek *et al.* 2015; Rajamurugan *et al.* 2017), but some negative effects (Ribeiro *et al.* 2019) of fragment size on woody species richness in the arboreal layer have been reported.

We found that species richness, species diversity and evenness were greater at the edge of both small and large forest fragments. However, we predicted that the richness and diversity of herbaceous species in the interior would be greater than at the forest edge. The positive edge influence that we found is probably because forest edges are heterogeneous environments suitable for a broad range of species (Ewers and Didham 2006). In addition, edge influence may be due to changes in environmental conditions at the forest edge such as greater light availability and penetration of light even in the sparse canopy (Harper *et al.* 2004; Jung *et al.* 2017), which increases species richness of the herb layer at the forest edge. This can also be a result of the occupation by different pioneer species at forest edges (Machado *et al.* 2017). Normann *et al.* (2016) also found that the richness of the herb

Table 2: Magnitude (MEI) and distance of edge influence (DEI) for species diversity indices and soil properties in small and large fragments

	Small fragments		Large fragments	
	MEI	**DEI (m)**	**MEI**	**DEI (m)**
Species richness	0.168	0, 50	0.247	0–25
Diversity	0.691	0, 50	0.097	0–25
Evenness	0.057	0	0.088	0–25
Phosphorus	0.499	0–25	0.226	n.s
Potassium	0.227	0–25	0.104	25–50
Organic carbon	−0.150	0–25	−0.326	0–50
Soil moisture	0.024	25	−0.036	0
Nitrogen	−0.139	0	−0.310	0–50
pH	−0.009	n.s	−0.028	50

Table 3: *P*-values of the generalized linear mixed models of the effects of distance from edge and fragment size on species diversity indices and soil properties

Variables	**Fragment size**	**Distance from edge**	**Fragment size × distance from edge**
Species richness	0.000***	0.000***	0.014*
Evenness	0.000***	0.000***	0.077
Diversity	0.002**	0.000***	0.011*
Phosphorus	0.803	0.000***	0.017*
Potassium	0.919	0.000***	0.003**
Organic carbon	0.000***	0.000***	0.000***
Nitrogen	0.000***	0.000***	0.000***
Soil moisture	0.315	0.061	0.199
pH	0.000***	0.052	0.533

$^*P < 0.05$, $^{**}P < 0.01$, $^{***}P < 0.001$.

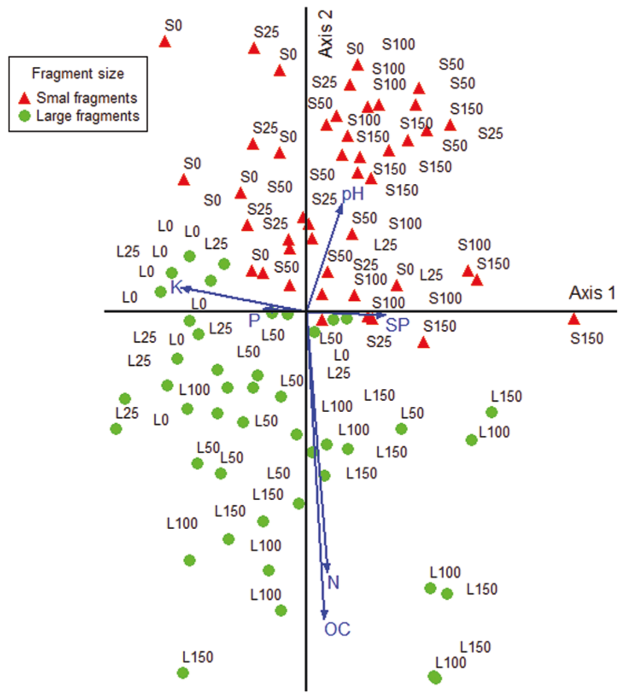

Figure 6: Non-metric multidimensional scaling ordination of sampling points in small (S, <10 ha) and large fragments (L, >10 ha). Numbers after S or L indicate the distance from the edge (0, 25, 50, 100 or 150 m). Arrows represent correlations between sampling point scores on the first two axes and soil properties (OC: organic carbon, N: nitrogen, P: phosphorus, SP: saturation point of soil moisture, K: potassium).

Table 4: Pearson correlation coefficients between the non-metric multidimensional scaling ordination axes and soil attributes

	Axis 1	Axis 2
Phosphorus	0.05	0.05
Potassium	−0.002	0.16
Organic carbon	0.42**	−0.50**
Nitrogen	0.39**	−0.46**
Soil moisture	0.05	−0.05
pH	−0.27	0.32

**Correlation is significant at the $P = 0.01$ level with a two-tailed test.

layer decreased with increasing distance from the forest edge in beech-dominated forest in Germany. In addition, greater species richness and diversity of the herb layer at the forest edge was found for pine forest of France (Alignier *et al.* 2014) and there was no significant edge influence on the abundance of herbaceous species in black spruce boreal forest in Canada (Harper *et al.* 2016). The response pattern of herbaceous species along the edge-to-interior forest gradient in open canopy oak forests is different from other ecosystems. Furthermore, the opposite trend of greater species richness in the interior compared to forest edge has also been found for the tree layer (Mendes *et al.* 2016; Ruwanza 2019), and no edge influence on tree species richness and composition was reported in southwestern Amazon forests (Phillips *et al.* 2006).

The DEI in this study is estimated to be 50 and 25, respectively, in small and large fragments for all diversity indices within the range found in other studies such as 50 m for diversity indices in temperate forests (Honnay *et al.* 2002). DEI was ~40 m for understory responses such as saplings and herb densities in boreal forest (Harper and Macdonald 2001). Franklin *et al.* (2021) found an average DEI of 42 m for a number of studies on vegetation at anthropogenic induced forest edges in the past three decades (Franklin *et al.* 2021). DEI estimates for understory responses and composition were generally greater than those for overstory response variables or forest structure (Franklin *et al.* 2021; Harper and Macdonald 2002; Harper *et al.* 2005). There have been fewer edge influence studies in open canopied forests, because edge influence is expected to be weaker, but that is changing with more studies in different ecosystems (Mendonça *et al.* 2015).

CONCLUSIONS

In sparse open canopy oak forests, anthropogenically created edges positively affect herbaceous species diversity and soil properties in small and large fragments. The effects of fragmentation on herbaceous species richness, diversity and composition were greater in small *vs.* large oak forest fragments due to both the greater amount of forest edge-affected area and deeper penetration of edge influence in smaller fragments. The majority of changes in herbaceous species richness and soil properties occurred within 50 m of the edge in both small and large oak sparse forest fragments. Even in open canopy forests, it is important to reduce direct impacts caused by edge influence on soil properties and species richness and diversity, especially in small fragments. Overall sparse oak forest interior habitat, both in small and large fragments, is being affected by edge influence. Therefore, we need urgent forest management strategies to conserve herbaceous species such as protective planting to prevent continuous disturbance or connecting small fragments to minimize edge influence. Different patterns of fragmentation effects on plant diversity for the herbaceous layer compared to the arboreal layer should be taken into account for management decisions.

Supplementary Material

Supplementary material is available at *Journal of Plant Ecology* online.

Table S1: The frequency (% of quadrats) of the 112 herbaceous species in small and large fragments.

Table S2: Mean, standard deviation (SD) at each distance and magnitude of edge influence (MEI) for species diversity indices and soil properties at each distance from the edge in small and large fragments; *P*-values are for the significance that the mean is different from interior forest (100 and 150 m from the edge, 2-tailed test).

Table S3: Result of the generalized linear mixed model of the effects of distance from the edge and fragment size on species diversity and soil properties ($P(>|Z|) < 0.05$).

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REFERENCES

Alignier A, Alard D, Chevalier R, *et al.* (2014) Can contrast between forest and adjacent open habitat explain the edge effects on plant diversity? *Bot Lett* **161**:253–259.

Arroyo-Rodríguez V, Saldana-Vazquez RA, Fahrig L, *et al.* (2017) Does forest fragmentation cause an increase in forest temperature? *Ecol Res* **32**:81–88.

Bates D, Mächler M, Bolker B, *et al.* (2014) Fitting linear mixed-effects models using lme4. arXiv:1406.5823.

Bennett AF, Saunders DA (2010) Habitat fragmentation and landscape change. *Conserv Biol* **93**:1544–1550.

Billings SA, Gaydess EA (2008) Soil nitrogen and carbon dynamics in a fragmented landscape experiencing forest succession. *Landscape Ecol* **23**:581–593.

Bremner JM (1960) Determination of nitrogen in soil by the Kjeldahl method. *J Agric Sci* **55**:11–33.

Brenes-Arguedas T, Roddy AB, Coley PD, *et al.* (2011) Do differences in understory light contribute to species distributions along a tropical rainfall gradient? *Oecologia* **166**:443–456.

Bunyan M, Jose S, Fletcher R (2012) Edge effects in small forest fragments: why more is better. *Am J Plant Sci* **3**:869–878.

Cong WF, Van Ruijven J, Mommer L, *et al.* (2014) Plant species richness promotes soil carbon and nitrogen stocks in grasslands without legumes. *J Ecol* **102**:1163–1170.

Dodonov P, Harper, KA, Xavier RO, *et al.* (2019) Spatial pattern of invasive and native graminoids in the Brazilian cerrado. *Plant Ecol* **220**:741–756.

Elzinga C, Salzer D, Willoughby J (1998) *Measuring and Monitoring Plant Populations*. Denver, CO: U.S. Department of the Interior Bureau of Land Management.

Eshaghi Rad J, Valadi G, Salehzadeh O, *et al.* (2018) Effects of anthropogenic disturbance on plant composition, plant diversity and soil properties in oak forests, Iran. *J For Sci* **64**:358–370.

Ewers RM, Didham RK (2006) Confounding factors in the detection of species responses to habitat fragmentation. *Biol Rev* **81**:117–707.

Fahrig L (2013) Rethinking patch size and isolation effects: the habitat amount hypothesis. *J Biogeogr* **40**:1649–1663.

Fletcher RJ, Ries L, Battin J, *et al.* (2007) The role of habitat area and edge in fragmented landscapes: definitively distinct or inevitably intertwined? *Can J Zool* **85**:1017–1030.

Franklin CMA, Harper KA, Clarke MJ (2021) Trends in studies of edge influence on vegetation at human-created and natural forest edges across time and space. *Can J For Res* **51**:274–282.

Ghahraman A (2001) *Iran's Flora*. Tehran, Iran: Forests of Iran, Research Institute of Forests and Rangelands Press.

Haddad NM, Brudvig LA, Clobert J, *et al.* (2015) Habitat fragmentation and its lasting impact on Earth's ecosystems. *Sci Adv* **1**:e1500052.

Harper KA, Danby RK, De Fields DL, *et al.* (2011) Tree spatial pattern within the forest–tundra ecotone: a comparison of sites across Canada. *Can J For Res* **41**:479–489.

Harper KA, Drapeau P, Lesieur D, *et al.* (2016) Negligible structural development and edge influence on the understory at 16–17-yr-old clear-cut edges in black spruce forest. *Appl Veg Sci* **19**:462–473.

Harper KA, Lesieur D, Bergeron Y, *et al.* (2004) Forest structure and composition at young fire and cut edges in black spruce boreal forest. *Can J Forest Res* **34**:289–302.

Harper KA, Macdonald SE (2001) Structure and composition of riparian boreal forest: new methods for analyzing edge influence. *Ecology* **82**:649–659.

Harper KA, Macdonald SE (2002) Structure and composition of edges next to regenerating clear-cuts in mixed-wood boreal forest. *J Veg Sci* **13**:535–546.

Harper KA, Macdonald SE, Burton PJ, *et al.* (2005) Edge influence on forest structure and composition in fragmented landscapes. *Conserv Biol* **19**:768–782.
Harper KA, Macdonald SE, Mayerhofer MS, *et al.* (2015) Edge influence on vegetation at natural and anthropogenic edges of boreal forests in Canada and Fennoscandia. *J Ecol* **103**:550–562.
Honnay O, Verheyen K, Hermy M (2002) Permeability of ancient forest edges for weedy plant species invasion. *Forest Ecol Manag* **161**:109–122.
Jazireiy M, Ebrahimi Rastaghi M (2013) *Zagros Silviculture*. Tehran, Iran: Tehran University Press.
Jung SH, Lim CH, Kim AR, *et al.* (2017) Edge effects confirmed at the clear-cut area of Korean red pine forest in Uljin, eastern Korea. *J Ecol Environ* **41**:36.
Kacholi DS (2014) Edge-interior disparities in tree species and structural composition of the Kilengwe forest in Morogoro region, Tanzania. *ISRN Ecol* **2014**:873174.
Koszelnik-Leszek A, Podlaska M, Fudali E, *et al.* (2015) Diversity of the midfield forest island's flora in the rural landscape of the south-western Poland in relation to sociological-ecological groups. *Zesz Nauk Uniw Przyr Wroc* **113**:29–55.
Laurance WF, Ferreira LV, Rankin-de Merona JM, *et al.* (1998) Rain forest fragmentation and the dynamics of Amazonian tree communities. *Ecology* **79**:2032–2040.
Laurance WF, Nascimento HE, Laurance SG, *et al.* (2006) Rain forest fragmentation and the proliferation of successional trees. *Ecology* **87**:469–482.
Ma L, Huang M, Shen Y, *et al.* (2015) Species diversity and community structure in forest fragments of Guangzhou, South China. *J Trop For Sci* 148–157.
Machado FS, de França ACM, dos Santos RM, *et al.* (2017) Influence of the edge effect on a soil seed bank of a natural fragment in the Atlantic Forest. *Iheringia Ser Bot* **72**:247–253.
Magnago LFS, Magrach A, Barlow J, *et al.* (2017) Do fragment size and edge effects predict carbon stocks in trees and lianas in tropical forests? *Funct Ecol* **31**:542–552.
Magurran AE (2004) *Measuring Biological*. Oxford: Blackwell Publishing, 105.
McCune B, Mefford MJ (1999) *PC-ORD Multivariate Analysis of Ecological Data, Version 4*. Gleneden Beach, OR: MjM Software Design.
Mendes PGA, Silva MAM, Guerra TNF, *et al.* (2016) Dynamics and edge effect of an Atlantic forest fragment in Brazil. *Flor Amb* **23**:340–349.
Mendonça AH, Russo C, Melo ACG, *et al.* (2015) Edge effects in savanna fragments: a case study in the cerrado. *Plant Ecol Divers* **8**:493–503.
Muchiru AN, Western D, Reid RS (2009) The impact of abandoned pastoral settlements on plant and nutrient succession in an African savanna ecosystem. *J Arid Environ* **73**:322–331.
Mullu D (2016) A review on the effect of habitat fragmentation on ecosystem. *J Nat Sci Res* **6**:1–15.
Normann C, Tscharntke T, Scherber C (2016) How forest edge-center transitions in the herb layer interact with beech dominance versus tree diversity. *J Plant Ecol* **9**:498–507.
Oksanen J, Blanchet FG, Kindet R, *et al.* (2012) *vegan: Community Ecology Package, R Package Version 2.0-4*. UK: Pelagic publishing.
Olsen SR (1954) *Estimation of Available Phosphorus in Soils by Extraction with Sodium Bicarbonate*. Circular, Vol. **939**. Washington, DC: US Department of Agriculture, 1–19.
Phillips OL, Rose S, Mendoza AM, *et al.* (2006) Resilience of southwestern Amazon forests to anthropogenic edge effects. *Conserv Biol* **20**:1698–1710.
Piper CS (1944) *Soil and Plant Analysis: A Laboratory Manual of Methods for the Examination of Soils and the Determination of the Inorganic Constituents of Plants (No. 8)*. New York: Interscience Publishers.
Rajamurugan J, Mohandass D, Jayakrishnan P, *et al.* (2017) Impact of fragment size on woody species richness and abundance of sacred groves in south-east India. In: *National Seminar on "Biodiversity Conservation and Sustainable Utilization" (NSBCS 2017), Department of Botany, Bharathiar University, Coimbatore, Tamil Nadu, India*, 20–21 March 2017.
Rantalainen ML, Haimi J, Fritze H, *et al.* (2008) Soil decomposer community as a model system in studying the effects of habitat fragmentation and habitat corridors. *Soil Biol Biochem* **40**:853–863.
R Core Team (2014) *R: A Language and Environment for Statistical Computing*. Vienna, Austria: R Foundation for Statistical Computing. http://www.R-project.org/
Ribeiro JT, Nunes-Freitas AF, Uzêda MC (2019) Forest fragmentation and impacts of intensive agriculture: responses from functional groups of the tree community. *bioRxiv* DOI:10.1101/546796.
Robinson WD, Sherry TW (2012) Mechanisms of avian population decline and species loss in tropical forest fragments. *J Ornithol* **153**:141–152.
Rogan JE, Lacher TE (2018) Impacts of habitat loss and fragmentation on terrestrial biodiversity. In: *Reference Module in Earth Systems and Environmental Sciences*. London, UK: Elsevier Press, 1–18.
Rovai AP, Baker JD, Ponton MK (2013) *Social Science Research Design and Statistics: A Practitioner's Guide to Research Methods and IBM SPSS Analysis*. Chesapeake, VA: Watertree Press.
Ruwanza S (2019) The edge effect on plant diversity and soil properties in abandoned fields targeted for ecological restoration. *Sustainability* **11**:140.
Santana LD, Prado-Junior JA, Ribeiro JHC, *et al.* (2021) Effects in forest patches surrounded by native grassland are also dependent on patch size and shape. *Forest Ecol Manag* **482**:118842.
Shen C, Ma L, Hu J, *et al.* (2019) Soil carbon storage and its determinants in forest fragments of differentiated patch size. *Forests* **10**:1044.
Walkley A, Black IA (1934) An examination of the Degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method. *Soil Sci* **37**:29–38.