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Spatial Comparative Analysis of Landscape Fragmentation Metrics in a Watershed with Diverse Land Uses in Iran

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Abstract: Knowledge of landscape fragmentation is known to be important in ecological integrity, hydrological processes, urban planning, sustainable land management, and policymaking. Recent anecdotal studies reveal a need for analytical quantification of landscape fragmentation at different levels. Therefore, the present study was conducted at KoozehTopraghi Watershed, Ardabil Province, Iran, where covers by different land uses/covers, to (a) explore the spatial pattern of landscape fragmentation metrics comprehensively in different scales, (b) distinguish the landscape fragmentation hot spots, and (c) investigate the spatial clustering of landscape fragmentation metrics. The behaviors of 7, 10, and 13 fragmentation metrics concerning three levels of patch, class, and landscape across 36 sub-watersheds were explored using principal component analysis (PCA) and expert elicitation. The Getis-Ord Gi* and local Moran's I indices were also used to analyze the hot spots and clusters of landscape fragmentation, respectively. The results verified the high degree of spatial variability of the metrics in the three levels of fragmentation analysis. The class-level fragmentation analysis showed that the watershed is characterized by high-fragmented residential land use and low-fragmented dry farming land use. The spatial trend analysis at the landscape level further indicated that sub-watersheds 1, 2, 11, 21, to 26, and 34 to 36, mainly located in lowlands and central parts, allocated better status considering the fragmentation metrics rather than other parts of the watershed. The significant hot spots and high clusters of fragmentation also were distributed in different parts of the watershed in terms of various landscape metrics.

Keywords: clustering; hot spot analysis; land management; land use pattern

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1. Introduction

During the past three decades, rising human needs have resulted in a significant increase in land use changes and damages [1,2]. Concerns over the effect of changing land use patterns resulting from deforestation and agricultural development or elimination have caused a crisis in the quality of water and soil resources [3]. Since economic and human activities are mainly carried out on the landscape, it is considered an appropriate spatial scale for studying the environmental changes caused by human activities during a long-term period [1]; therefore, the assessment of landscape changes and reflection on the human use of the land in the past are used as dynamic tools for sustainable land use planning [4]. In this context, the landscape metrics are introduced as algorithms for quantifying the spatial properties of patches, classes, or mosaics of the entire terrestrial landscape. Landscape metrics are the best way to compare the state of the landscape of different land uses (e.g., [4–7]). The use of landscape metrics plays an important role in determining the different features of land use types relative to each other. Additionally, they can help to monitor better the impact of land use changes on hydrological processes and nutrient cycles [8]. Therefore, knowledge of human activities' impacts in different sectors or land use types, as primary data in spatial–temporal characteristics of landscape analysis, is of particular importance to land changes interpretation and modeling and understanding the relations between environmental and human factors [4].

Landscape fragmentation is one of the most critical processes representing human activities' impact on the land structure and function disruption [2]. In the fragmentation process, the landscape is divided into smaller patches which refers to the landscape transformation for human use that hurts biodiversity. It is one of the significant implications of land degradation in reducing dominant communications and habitat corridors over the landscape [9–11]. The analysis of landscape fragmentation can lead to effective development strategies to better land reconstruction and conservation [12].

Many studies have been performed regarding the importance of examining land use changes and landscape fragmentation. For example, Amsalu et al. [13] studied the land use change in the Ethiopian Highlands watersheds. They reported a reduction trend in natural vegetation due to forest conversion to agriculture due to policy changes that took place over 40 years. Furthermore, Aspinall and Hill [14] reviewed the land use changes and management in the Amazon Forest. They reported a significant forest fragmentation process. Their results also indicated a reducing trend in the average size of patches and the total forest length, as well as an increase in the distance between the forest patches due to forest degradation and land use change. Giraldo [15] also investigated the spatial scale of land use fragmentation in monitoring the water process in Colombia. In this study, using remote sensing (RS) and geographical information system (GIS), statistical analysis, and comparison of man-fabricated patches, a variety of landscape patches were studied. The results indicated the significant effect of landscape fragmentation on hydrological processes. In Japan, Kang et al. [16] calculated the Shannon diversity index, dominance index, mean patch size, edge density, patch density, and mean patch size in 1888, 1909, 1961, and 2002. They concluded that the landscape diversity was reduced, and urban areas, pasture, rice fields, and rangelands were increased, which was attributed to large and split patches.

Nohegar et al. [8] analyzed the land use characteristics in the central part of Guilan. They used 16 metrics to interpret and analyze the landscape structure. The results showed that the impact of human interference decreased the landscape structure and connectivity, which reflected very high forest utilization and agricultural evolution. Additionally, in the Sefidrud, northern Iran, Kiyani and Feghhi [17] calculated different landscape metrics, including the class area, area percentage, patch number, total edge, landscape shape, the largest patch, the average landscape of the patch, mean patch area, and Euclidean nearest neighbor distance. They concluded that the highest and lowest fragmentation occurred in agricultural and forest land uses, respectively. The highest and lowest patches dispersion was also related to pasture and forest land uses in that respect. Mitchell et al. [18] also examined the landscape fragmentation effect of the ecosystem services in Brazil concerning economic, social, and political dimensions. The results verified both positive and negative effects of fragmentation on ecosystem services. Subsequently, De Montisa et al. [1] examined the landscape fragmentation in Mediterranean Europe. They used three indicators, including indices of infrastructure fragmentation, urban symmetry, and connectivity. The results showed that the coastal areas face high-pressure utilization, and the fast transport infrastructure and new settlements showed the highest fragmentation rates.

Lam et al. [12] explored the effect of landscape fragmentation on land losses in the Louisiana coastline, United States, based on Landsat TM+ images from 1996 to 2010. The results showed significant land loss due to the fragmentation effects. Kowe et al. [3] determined the hot and cold spots and clusters of fragmentation during 1994–2017 in Harare metropolitan city, Zimbabwe. The highly fragmented patterns of vegetation patches detected as cold spots were mainly located in the densely built-up places of the study city (i.e., western, eastern, and southern parts). The long-term viability of the Natura

2000 (N2k) network as the world's largest coordinated network of protected areas was evaluated by Lawrence et al. [19]. They quantified the degree to which N2k sites are insulated from development pressures and found that the anthropogenic pressures lead to the fragmentation of protected areas. Forest fragmentation of Chitteri Hills in India was analyzed by Narmada et al. [9]. The results showed an increase in the number of patches due to the expansion of the urban population during the 2000–2019 period. In addition, the effects of surrounding areas on the landscape fragmentation of national parks were assessed by Kubacka et al. [2]. According to their findings, the high natural and landscape values in the surrounding areas of national parks affect the degree of landscape fragmentation. Meanwhile, the patch density index was assessed as a suitable indicator to indicate the dynamic nature of the landscape change.

In general, different studies were conducted for quantifying landscape metrics; however, their analysis at different levels of the patch, class, and landscape, which is essential for the interpretation and comparison of the regional landscape structure, was not well-considered. KoozehTopraghi Watershed, with diverse land uses located in the northwest of Iran, is similar to many other areas threatened by human activities such as land use change. To this end, the extent, intensity, and spatial pattern of landscape fragmentation in this watershed are under question. In addition, another key question is how landscape metrics at different levels of landscape fragmentation behave. The third critical question that remains unanswered in the watershed study point where the hot spots and cold spots of landscape fragmentation metrics are. Towards this, the present study aims to evaluate the spatial variation in land fragmentation metrics in three levels of patch, class, and landscape in the KoozehTopraghi Watershed, Iran. Furthermore, the landscape fragmentation hot spots and the spatial clustering of landscape fragmentation metrics were investigated. The results can be the appropriate tools to monitor landscape changes and land use-related management decisions.

2. Materials and Methods

2.1. Study Area

KoozehTopraghi Watershed (48°2′ to 48°31′ E, 37°46′ to 38°8′ N) with a total area and perimeter of 802.98 km^2 and 1489 km, respectively, is located in the southern part of Ardabil Province. The residential areas of the watershed are comprised of 65 villages. The cold semi-arid climate (Köppen: BSk) is dominant in the area. According to the statistical information of 40 years, the mean annual rainfall and temperature of the watershed are 300 mm and 6.95 °C. Moreover, the lowest and highest altitude of the watershed is 1378 and 2549 m, respectively. The watershed is further divided into 36 sub-watersheds. Figure 1 shows the general view of the KoozehTopraghi Watershed in Iran and Ardabil Province [20].

2.2. Methodology

2.2.1. Land Use Mapping

In this research, maps of topography (1:25,000) and Google Earth images of 2018 for the KoozehTopraghi Watershed were prepared for land use map generation. The main basis of the land use map generation was Google Earth images because of their high resolution, high precision, and eye-wise interpretation of them [17,21]. Visual interpretation of the image and information from previous research is adapted as two main tools to control the accuracy of the prepared land use map [4]. All these analyses were performed using ArcGIS 10.8 and Google Earth Pro 7.3.2.5491 software. According to the conducted analysis, the KoozehTopraghi Watershed has allocated different land uses, viz. dry farming, moderate rangeland, good rangeland, irrigation, rock, orchard, residential, and water body as tabulated and depicted in Table 1 and Figure 2.

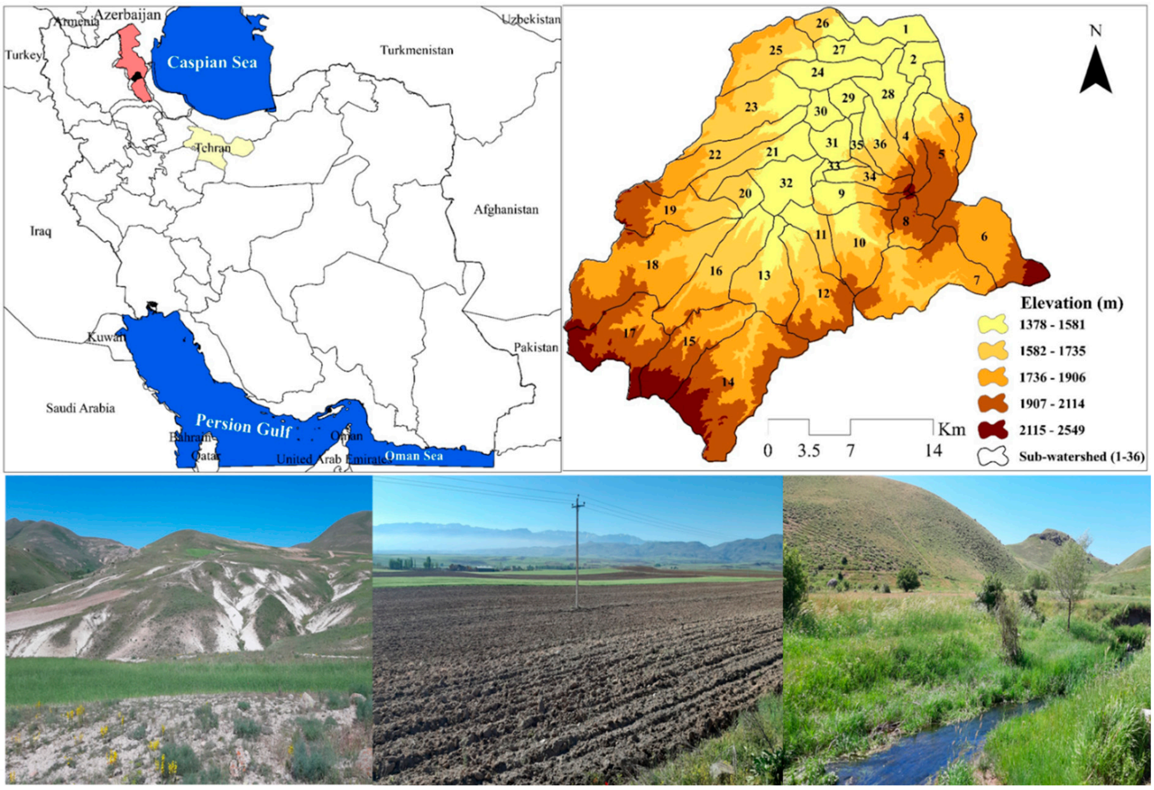


Figure 1. Location map of KoozehTopraghi Watershed, Ardabil Province, Iran.

Table 1. Type, area, and percent of land use of the KoozehTopraghi Watershed, Ardabil Province, Iran.

Land Use Type	Area (km^2)	Percent (%)
Dry farming	465.33	57.95
Moderate rangeland	194.71	24.25
Good rangeland	74.27	9.25
Irrigation	28.17	28.17
Rock	20.36	1.53
Orchard	12.3	12.30
Residential	6.07	0.76
Water body	1.77	0.22
Sum	802.98	100

2.2.2. FRAGSTATS Software Application

One of the tools for the calculation of landscape metrics is FRAGSTATS Software. This software is more commonly used as a function of the ability to calculate a wide range of landscape metrics. FRAGSTATS Software has no limitations in scale and magnification and is suitable for analyzing the spatial pattern of the landscape patches in heterogeneous environments and different conditions [22,23]. Towards this, for the present study, FRAGSTATS Software 4.2 (Landscape Ecology Lab, University of Massachusetts Amherst, Amherst, MA, USA) [24] was run for developing three output files of patch, class, and landscape metrics, all of which are visible as text files [9,10]. For developing the study metrics, the vector-based map of land use which was generated for KoozehTopraghi Watershed transformed into Raster format. Hence, all FRAGSTATS analyses were performed at 36 sub-watersheds of KoozehTopraghi.

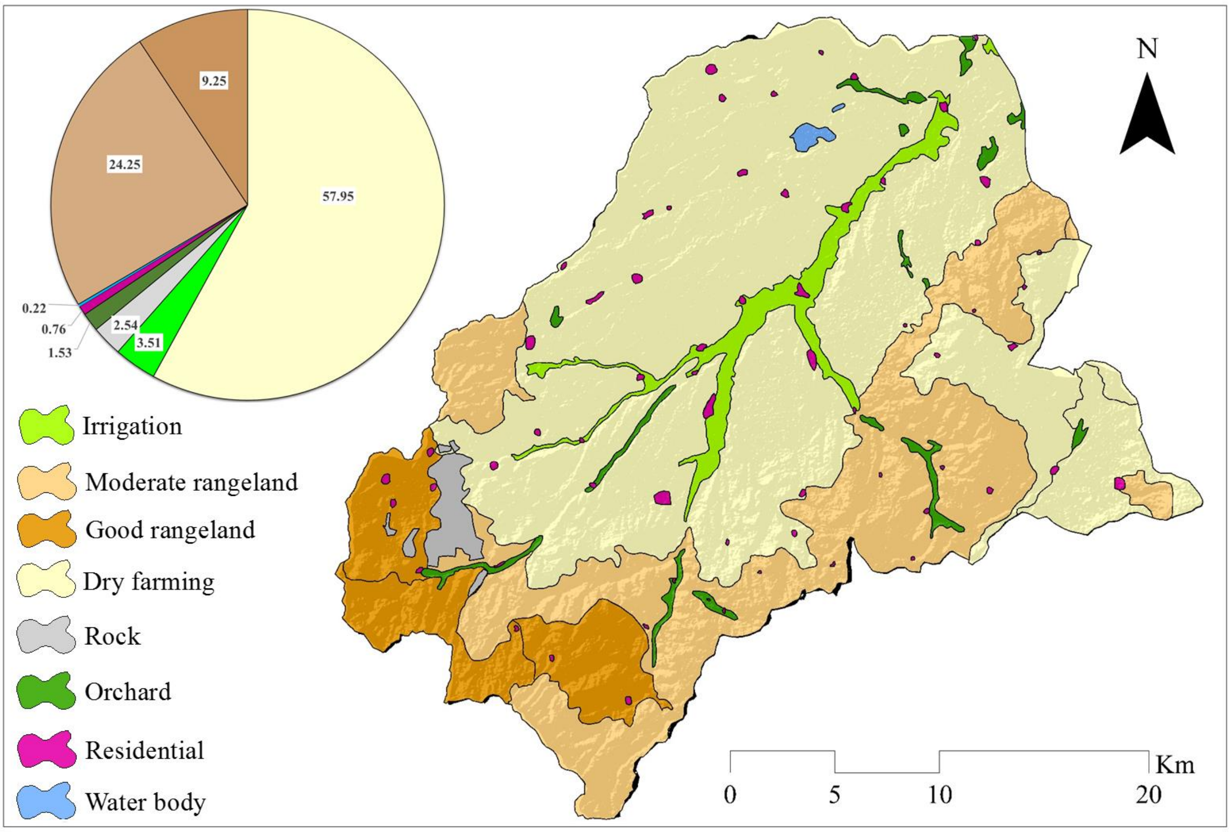


Figure 2. Land use patterns of KoozehTopraghi Watershed, Ardabil Province, Iran in 2018.

2.2.3. Landscape Metrics Selection

Choosing the appropriate metrics among many metrics is a crucial step to effectually being aware of minimal numbers of impressive metrics with maximal effectiveness [25]. Some metrics overlap and present similar information on a specific landscape status [26]. Therefore, principal component analysis (PCA) as a type of statistical analysis was used to help select the most important metrics and thus eliminate some of the insignificant ones [27]. In the present study, in addition to the PCA results, the correlation coefficient and expert opinion were also used as auxiliary tools to this end. The experts were selected from professors and students (five persons) who have special research in this field and are familiar with the KoozehTopraghi Watershed. The point of view of the experts was acquired and considered through personal meetings. This study attempted to have representative metrics from all four features of edge, aggregation, shape, and diversity in each level of patch, class, and landscape.

The PCA method was performed in IBM SPSS statistics 25.0 software (University of Stanford, Stanford, CA, USA). In addition, this software with the help of Excel 2016 was used for component coding and standardizing steps and unit variance, correlation matrix, Eigenvalues, and Eigenvector eliminating components that justify a lower percentage of the data variance. Finally, the preparation of component variables and Varimax rotation were performed to determine the main components of each study level [28,29]. Generally, to analyze the landscape patterns of the KoozehTopraghi Watershed, the correlation is determined between landscape metrics. At patch, class, and landscape levels, 7, 10, and 13 metrics were selected, respectively, out of 40, 40, and 70 available metrics. The calculations of the selected metrics in each study level are described in Appendix A (Tables A1–A3).

2.2.4. Analysis of Hot Spots and Clustering

The fragmentation hot spots and cold spots throughout the study watershed were using Getis-Ord Gi* statistic as provided in Equation (1) [30,31].

$$\text{Gi}^* = \sum_{j\neq i} j * i^{w_{ij}x_j - w_i\bar{x}} \Bigg/ s\sqrt{\frac{ns_{1i} - w_i^2}{n-1}} \tag{1}$$

where w_i^* is the sum of w_{ij} and w_{ij} shows the binary weighting matrix for the adjacent spaces. The mean and standard deviations of landscape fragmentation values are dedicated as $\bar{x}$ and s, respectively. Using ArcGIS 10.8, when calculating this index, a z-score is generated, and it shows the high or low spatial clusters.

High- and low-value clustering of fragmentation was also mapped using Local Moran's I as provided in Equation (2) [32,33].

$$\text{I(d)} = \frac{\frac{1}{\text{W}}\sum_{\text{h}=1}^{\text{n}}\sum_{\text{i}=1}^{\text{n}} \text{w}_{\text{hi}}(\text{z}_{\text{h}} - \bar{\text{z}})(\text{z}_{\text{i}} - \bar{\text{z}})}{\frac{1}{\text{n}}\sum_{\text{i}=1}^{\text{n}}(\text{z}_{\text{i}} - \bar{\text{z}})^2} \tag{2}$$

where W, n, and w_{hi}, are indicated by the number of pairs of points having distances within the distance class, the total number of points, and the weight function, respectively. The w_{hi} = 1 means the points *h* and *i* are within the distance class. The Moran index is varied between −1 to +1. Its minimum and maximum limits denote the highly dispersed and highly clustered patterns, respectively. The random patterns are also determined by Local Moran's I of zero.

3. Results

3.1. Patch-Level Metrics

The results of FRAGSTATS to quantify the fragmentation metrics of KoozehTopraghi Watershed at the patch level were obtained. The patch-level metrics were computed as one for each patch in the mosaic. By incorporating the FRAGSTATS results into ArcGIS 10.8, the spatial distribution using the spatial analyst tool at patch-level metrics in KoozehTopraghi Watershed was tabulated in Table 2. The seven metrics of AREA_CPS, AREA_LPS, PERIM, GYRATE, SHAPE, FRAC, and CIRCLE were selected out of 40 metrics at the patch level according to PCA and expert analyses for fragmentation characterization of the study watershed.

The mean value of the AREA_CPS metric for the KoozehTopraghi Watershed was obtained between zero (very highly fragmented) to 46.15% (moderately fragmented) out of 100. The AREA_CPS of 100 shows no fragmentation. The highest value of the AREA_CPS metric was attributed to sub-watersheds 10 and 14, where the altitude is included in different classes and located in southern parts. Sub-watershed 10 is mainly formed from land uses of orchard (16.66%), moderate rangeland (25.00%), dry farming (41.66%), and residential (16.66%). In addition, the land use of sub-watershed 14 is comprised of the orchard (16.66%), moderate rangeland (25.00%), dry farming (16.66%), residential (41.66%), and good rangeland (0.00%). Furthermore, the results of the AREA_CPS metric analysis also indicated the lowest value of zero for sub-watersheds 21 and 23 located in the northwestern parts, as described in Table 2.

Table 2. Results of patch-level metrics analysis in the KoozehTopraghi Watershed, Ardabil Province, Iran.

SW \ Metric	AREA_CPS	AREA_LPS	PERIM	GYRATE	SHAPE	FRAC	CIRCLE
1	35.71	50.00	8590.11	50.00	1.56	1.07	0.56
2	35.71	50.00	3636.52	249.42	1.36	1.06	0.49
3	41.67	50.00	7216.07	544.75	1.55	1.07	0.66
4	35.71	50.00	8590.11	548.03	1.56	1.07	0.56
5	35.71	50.00	8590.11	548.03	1.56	1.07	0.56
6	42.13	45.26	4864.68	292.45	1.39	1.05	0.44
7	40.00	47.14	8113.71	519.31	1.57	1.05	0.41
8	42.86	50.00	4851.69	351.60	1.51	1.07	0.54
9	37.50	50.00	7004.95	505.73	1.46	1.05	0.51
10	46.15	50.00	5995.91	403.79	1.40	1.05	0.56
11	25.00	50.00	7972.26	605.60	1.60	1.07	0.67
12	28.57	50.00	10710.27	639.60	1.50	1.06	0.52
13	37.50	49.24	7302.62	402.33	1.58	1.07	0.56
14	46.15	49.36	11,855.43	650.73	1.65	1.07	0.53
15	37.50	50.00	12,564.10	796.54	1.64	1.06	0.57
16	38.48	40.67	4680.86	290.45	1.39	1.04	0.37
17	39.33	43.50	4104.57	283.83	1.30	1.04	0.48
18	41.18	46.71	6424.94	427.56	1.59	1.06	0.48
19	38.89	56.67	17,653.78	904.95	1.88	1.07	0.51
20	32.14	47.62	4349.08	309.09	1.67	1.08	0.53
21	0.00	50.00	20,281.91	1624.60	2.07	1.11	0.83
22	30.00	48.00	13,200.00	902.63	1.62	1.06	0.54
23	0.00	50.00	11,631.76	760.68	1.68	1.07	0.62
24	33.33	50.00	6571.59	466.42	1.29	1.04	0.50
25	16.67	50.00	9667.94	598.59	1.92	1.09	0.73
26	38.89	50.00	6537.64	435.55	1.59	1.07	0.60
27	42.86	50.00	3998.94	291.05	1.40	1.05	0.48
28	32.14	47.62	3323.73	211.62	1.26	1.04	0.43
29	25.00	50.00	9324.15	673.95	1.53	1.05	0.53
30	45.45	50.00	6783.38	422.33	1.45	1.05	0.51
31	33.33	50.00	3969.57	292.46	1.41	1.06	0.53
32	35.71	50.00	5255.83	385.30	1.57	1.07	0.63
33	33.33	50.00	6690.10	503.09	1.44	1.05	0.45
34	38.89	50.00	6549.05	392.35	1.68	1.08	0.58
35	33.33	50.00	6690.10	503.09	1.44	1.05	0.45
36	38.89	50.00	6549.05	392.35	1.68	1.08	0.58
Mean	34.33	49.22	7836.01	505.00	1.55	1.06	0.54
Standard Deviation	10.30	2.41	3703.53	265.90	0.17	0.01	0.09
Variance	106.00	5.82	13,716,100.58	70,701.52	0.03	0.00	0.01

The green and red cells indicate the best (least fragmented) and worst (most fragmented) states considering landscape fragmentation, respectively.

The results of fragmentation analysis at the patch level in the KoozehTopraghi Watershed showed that the AREA_LPS metric had a uniform distribution throughout the whole watershed. The value of this metric varied from 40.67 to 56.67%, indicating a moderate state of the watershed in the viewpoint of landscape fragmentation at the patch-level class (Table 2).

The minimum, maximum, and average PERIM metric through KoozehTopraghi Watershed were 20 and 21 m, respectively, as tabulated in Table 2. GYRATE reaches its extreme value when the patch encompasses the whole landscape as obtained for sub-watershed 21 with the value of 1624.60 m (Table 2). Furthermore, sub-watershed 1, with a GYRATE metric of the value of 50.00 m, had the worst state in terms of landscape fragmentation. The mean and standard deviation of the GYRATE metric for KoozehTopraghi Watershed were 495.71 and 261.46 m, respectively (Table 2).

The SHAPE metric is a widely used and straightforward metric for complexity assessment. The patch shape is a function of the complexity of its morphology rather than particular morphologies. The lowest value of this index (i.e., one) denotes the square shape of the patch, and then it increases without limit as the shape develops more irregularly. This index solved the size problem of the perimeter-area ratio by considering a constant for a square standard. According to Table 2, the value of the SHAPE metric varied from 1.30 (sub-watershed 17) to 2.07 (sub-watershed 21), which is greater than one in all sub-watersheds, which is relatively irregular given the patch shape in the whole study watershed.

FRAC metric described the shape complexity through a series of patch sizes. A fractal dimension above one for a two-dimensional patch obtained for a disappearance from Euclidean geometry verifies a complexity increase. Fractal dimensions, whatever the value of greater complexity, increase between patches. According to the results provided in Table 2, all the study sub-watersheds spanned with values of 1.03 to 1.09 did not have complex patch shapes. A low and high CIRCLE is attributed to the highly convoluted but narrow patch and narrow and elongated patch. As shown in Table 2, a relatively uniform state of CIRCLE with a mean value of 0.54 ± 0.09 was obtained for the KoozehTopraghi Watershed. The corresponding minimum and maximum of CIRCLE were about 0.37 and 0.83, respectively.

The results of patch-level metrics analysis can help to adapt the appropriate potential policy implications in the study watershed. The present study also clearly reveals the different behavior of the selected fragmentation metrics at the patch level throughout the whole KoozehTopraghi Watershed.

3.2. Class-Level Metrics

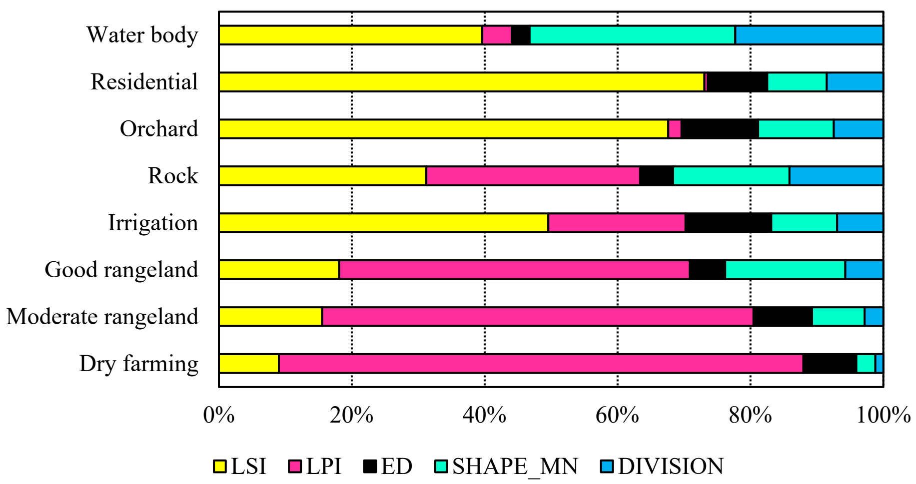
Table 3 shows the results of the class-level metrics of fragmentation analysis in the KoozehTopraghi Watershed. As can be seen from Table 3, the class-level metrics were generated in each land use type, and it could not process into the sub-watershed scale. Totally, 10 metrics among 40 calculated metrics by FRAFSTATS were selected based on the used methodologies for quantifying the fragmentation state of the study watershed at the class level as detailed in Figure 3.

The results showed that dry farming land use has the highest ED_C. This result verifies that the patches with dry farming (5.01 m ha^{-1}) followed by moderate rangeland (2.98 m ha^{-1}) in the study watershed are made of larger values indicating increased fragmentation compared with other land uses. The ED_C contains a user-specified proportion of internal background edge segments encompassing the corresponding patch type. About Table 3, the maximum and minimum ED_C is related to dry farming and water body, respectively. In Table 3, the LPI_C showed that although dry farming is dominant in the KoozehTopraghi Watershed and had the highest value of LPI_C (49.72%), the moderate rangeland with an LPI_C value of 21.95% also had a fragmented landscape.

Table 3. Results of class-level metrics analysis in the KoozehTopraghi Watershed, Ardabil Province, Iran.

Land Use	ED_C	LPI_C	$AREA\_MN_C$	TE_C	$SHAPE\_MN_C$	LSI_C	$COHESION_C$	$SPLIT_C$	$DIVISION_C$	PD_C
Dry farming	5.01	49.72	5916.66	406,050.00	1.81	5.69	99.66	3.93	0.75	0.01
Moderate rangeland	2.98	21.95	6490.50	241,500.00	2.68	5.26	99.27	20.63	0.95	0.00
Good rangeland	0.92	9.16	7427.25	74,250.00	3.14	3.14	98.78	119.23	0.99	0.00
Irrigation	1.86	2.98	117.38	151,200.00	1.43	7.15	96.19	1124.91	1.00	0.03
Rock	0.35	2.28	407.25	28,500.00	1.24	2.21	95.90	1909.08	1.00	0.01
Orchard	1.55	0.27	39.70	126,000.00	1.53	9.09	82.55	59193.68	1.00	0.04
Residential	1.05	0.06	8.80	84,900.00	1.05	8.58	55.26	640,020.70	1.00	0.09
Water body	0.12	0.20	88.88	9600.00	1.39	1.78	86.59	242,170.00	1.00	0.00
Mean	1.73	10.83	2562.05	140,250.00	1.78	5.36	89.28	118,070.27	0.96	0.02
Standard Deviation	1.50	16.26	3161.76	121,553.11	0.69	2.63	14.14	212,207.71	0.08	0.03
Variance	2.25	264.26	9,996,722.26	14,775,159,375.00	0.48	6.91	199.91	45,032,114,060.40	0.01	0.00

The green and red cells indicate the best (least fragmented) and worst (most fragmented) states considering landscape fragmentation, respectively.



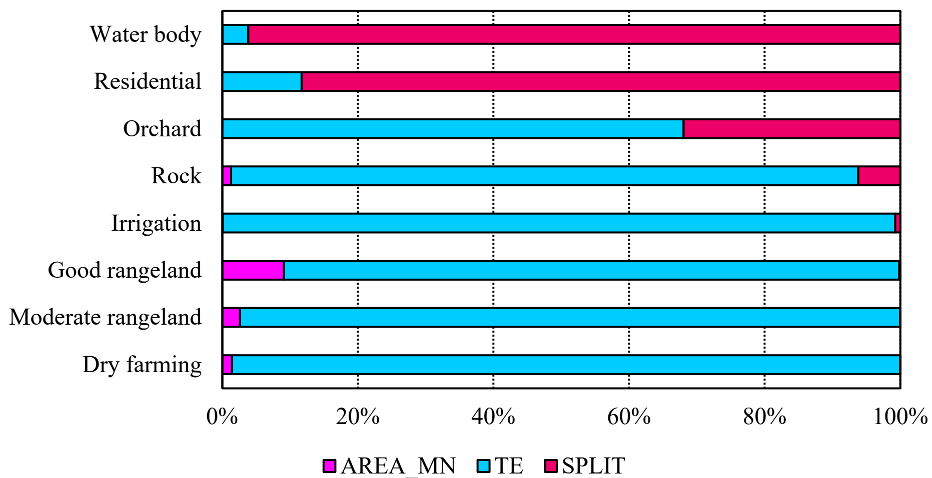


Figure 3. *Cont.*

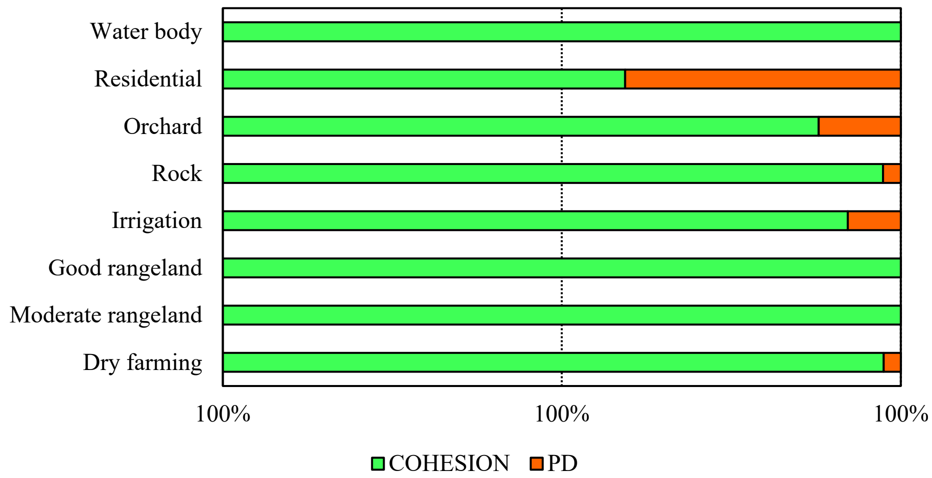


Figure 3. Results of class-level metrics analysis in the KoozehTopraghi Watershed.

For the KoozehTopraghi Watershed, $AREA\_MN_C$ indicates that the rangelands have more connectivity and cohesion with the lack of human interferences and the residential land use has the highest degree of fragmentation. It is found that the overall average of $AREA\_MN_C$ metric was 2562.05 ± 3380.06 ha varying from 8.80 ha in residential to 7427.25 ha in good rangeland land uses (Table 3). TE_C is an absolute measure of the total edge length of a patch type varied from 9600 (water body) to 406050 m (dry farming) with a mean and standard deviation of 140,250 and 121,553.11 m, respectively, in the KoozehTopraghi Watershed (Table 3). The $SHAPE\_MN_C$ obtained was greater than one in all sub-watersheds, which indicates the high irregularity of the patch shape. The mean and standard deviation of the $SHAPE\_MN_C$ metric was obtained at 1.78 and 0.73, respectively. Furthermore, the best and worst state of $SHAPE\_MN_C$ was observed in residential (1.05) and good rangeland (3.14), respectively. The maximum $COHESION_C$ was in dry farming (99.66) and the lowest amount was obtained for residential (55.26) land uses.

As shown in Table 3, the large variability of $SPLIT_C$ with a mean value of 118,070.27 ± 226,859.59 was obtained for the KoozehTopraghi Watershed. The corresponding minimal and maximal of $SPLIT_C$ were about 3.93 in dry farming and 640,020.70 in residential, respectively. The $DIVISION_C$ of the study watershed varied from 0.75 to 1 ha with a mean value of 0.96 ± 0.09 ha. The general spatial trend of SPLIT was in line with $DIVSION_C$ at a direct correlation. The rangeland and dry farming in the KoozehTopraghi Watershed had less connectivity and cohesion than other land uses in terms of $DIVISION_C$.

3.3. Landscape-Level Metrics

As explained in Table 4, 13 landscape-level metrics were evaluated to make a final determination about the sub-watershed classification and priority rank of KoozehTopraghi Watershed from the viewpoint of fragmentation.

For the study watershed, a mean ED_L metric of 7.27 ± 3 m ha^{-1} was found. Furthermore, the results suggested that sub-watersheds 21 and 27, with ED_L values of 0.83 and 13.85 m ha^{-1} at the landscape level were the least and most fragmented in the KoozehTopraghi Watershed (Table 4), respectively. The spatial pattern of LPI_L at the KoozehTopraghi Watershed, with a mean value of 69.78 ± 21.69%, indicated the relatively low level of fragmentation status in most sub-watersheds (more than 20 sub-watersheds). However, some parts of the watershed experienced highly critical conditions from the viewpoint of LPI_L (such as 9, 31, 32, etc.). According to Table 4, the value of LPI_L was attributed to sub-watershed 21 with a value of 99.35, where land use is dominated by irrigation (0.65%) and dry farming (99.35%); while the lowest LPI_L was allocated to sub-watershed 31 with a value of 33.70, which mainly included irrigation (98.99%), residential 0.01%), and dry farming (1%) land uses.

Table 4. Results of landscape-level metrics analysis in the KoozehTopraghi Watershed, Ardabil Province, Iran.

SW \ Metric	ED_L	LPI_L	$AREA\_MN_L$	TE_L	$SHAPE\_MN_L$	LSI_L	$COHESION_L$	$SPLIT_L$	$DIVISION_L$	PD_L	PRD	SHDI	MSIDI
1	7.16	91.55	217.49	9340.32	1.71	2.57	99.88	1.19	0.16	0.46	0.31	0.34	0.17
2	5.36	93.25	121.23	4550.81	1.36	1.79	99.80	1.15	0.13	0.82	0.35	0.29	0.14
3	4.79	34.45	222.07	6379.59	1.55	2.52	99.52	3.14	0.68	0.45	0.23	0.74	0.66
4	7.34	46.38	294.67	10,812.02	1.61	2.76	99.75	2.72	0.63	0.34	0.27	0.83	0.73
5	8.14	45.24	277.58	22,595	1.54	2.75	99.73	2.70	0.63	0.36	0.11	0.75	0.70
6	8.23	54.75	179.64	29,578.77	1.39	2.82	99.51	2.52	0.60	0.56	0.14	0.98	0.85
7	8.10	69.54	314.99	38,271.82	1.57	3.03	99.56	1.93	0.48	0.32	0.08	0.83	0.62
8	5.60	77.73	176.75	6932.02	1.51	1.92	99.64	1.58	0.37	0.57	0.24	0.56	0.43
9	10.35	38.43	182.76	15,134.26	1.46	2.67	99.57	4.05	0.75	0.55	0.27	0.77	0.50
10	8.12	66.26	230.25	24,316.34	1.40	2.45	99.56	2.04	0.51	0.43	0.17	0.82	0.65
11	2.13	94.78	328.51	2799.25	1.60	2.00	99.79	1.11	0.10	0.30	0.23	0.23	0.11
12	5.61	52.60	485.29	19,065.46	1.50	2.40	99.77	2.02	0.51	0.21	0.12	0.73	0.70
13	9.61	78.88	236.54	27,271.08	1.58	2.83	99.70	1.54	0.35	0.42	0.18	0.64	0.41
14	7.58	67.08	519.32	51,193.57	1.65	3.13	99.60	1.89	0.47	0.19	0.07	0.80	0.63
15	9.09	43.25	422.19	30,691.45	1.64	3.00	99.48	2.84	0.65	0.24	0.15	1.03	0.96
16	9.82	87.66	145.78	35,782.36	1.39	3.36	99.53	1.30	0.23	0.69	0.14	0.50	0.26
17	8.25	50.48	149.78	30,903.23	1.30	2.93	99.29	2.89	0.65	0.67	0.13	0.91	0.80
18	9.46	52.98	360.50	61,383.00	1.67	3.71	99.47	2.60	0.62	0.28	0.09	1.18	0.78
19	8.17	46.95	409.81	23,446.00	1.79	2.82	99.72	2.28	0.56	0.24	0.14	0.90	0.82
20	6.76	91.76	128.06	6059.63	1.67	2.03	99.69	1.18	0.15	0.78	0.33	0.26	0.14
21	0.83	99.35	1020.68	1699.01	2.07	2.15	99.95	1.01	0.01	0.10	0.10	0.04	0.01
22	4.99	88.17	417.51	12,510.00	1.57	2.83	99.78	1.27	0.22	0.24	0.24	0.49	0.24
23	1.77	98.98	649.57	5753.66	1.38	1.98	99.93	1.02	0.02	0.15	0.06	0.06	0.02
24	6.59	88.32	393.80	10,373.36	1.68	2.27	99.92	1.26	0.21	0.25	0.25	0.41	0.23
25	1.78	98.70	641.09	4572.39	1.32	1.76	99.94	1.03	0.03	0.16	0.08	0.07	0.03
26	1.45	99.33	308.04	1338.37	1.29	1.51	99.96	1.01	0.01	0.32	0.22	0.04	0.01
27	13.85	88.70	201.74	16,760.36	1.92	2.96	99.88	1.26	0.20	0.50	0.41	0.43	0.23
28	9.92	58.37	169.46	15,131.20	1.59	2.79	99.41	2.48	0.60	0.59	0.20	0.57	0.44
29	9.51	72.42	104.32	6943.37	1.40	1.95	99.59	1.77	0.43	0.96	0.41	0.58	0.42
30	5.42	93.32	104.28	3959.57	1.26	1.79	99.84	1.14	0.13	0.96	0.41	0.28	0.13
31	10.64	33.70	245.77	10,457.27	1.53	2.14	99.65	3.00	0.67	0.41	0.31	0.64	0.59
32	11.85	35.74	177.89	23,193.51	1.45	2.91	99.50	3.36	0.70	0.56	0.15	0.72	0.64
33	9.62	50.43	61.13	3529.91	1.41	2.65	99.62	2.63	0.62	1.64	0.82	0.71	0.61
34	7.92	73.92	309.87	12,335.15	1.51	2.37	99.71	1.80	0.33	0.62	0.30	0.42	0.32
35	7.96	74.19	310.70	12,040.57	1.51	2.36	99.72	1.79	0.33	0.63	0.31	0.41	0.31
36	8.00	74.46	311.53	11,745.99	1.51	2.35	99.72	1.78	0.32	0.64	0.31	0.40	0.30
Mean	7.27	69.78	300.85	16,912.49	1.54	2.51	99.69	1.95	0.39	0.49	0.23	0.57	0.43
Standard Deviation	2.96	21.38	186.10	13,890.26	0.17	0.49	0.17	0.79	0.23	0.29	0.14	0.29	0.27
Variance	8.78	457.25	34,634.27	192,939,422.56	0.03	0.24	0.03	0.62	0.05	0.09	0.02	0.08	0.07

The green and red cells indicate the best (least fragmented) and worst (most fragmented) states considering landscape fragmentation, respectively.

The results of the AREA_MN$_L$ for the present study were computed as 300.85 ± 188.74 ha. The large spatial variability was found for AREA–MN$_L$ significantly with a range of 61.15 (sub-watershed 33) to 1020.68 (sub-watershed 21) ha.

TE$_L$ at the landscape level is an absolute measure of the total edge length of all patch types. The maximum and minimum of TE$_L$ for KoozehTopraghi Watershed at landscape level were obtained for sub-watersheds 37 (61,383.00 m) and 21 (1338.37 m), respectively. SHAPE_MN$_L$ varied between 1.32 (sub-watershed 25) and 2.07 (sub-watershed 21). Since all the LSI$_L$ values of KoozehTopraghi sub-watersheds are more than one (Table 4), it can be concluded that the shape of the patches in all sub-watersheds is irregular. LSI$_L$ was found equal to 2.51 ± 0.5 with minimal and maximal values of 1.51 (sub-watershed 26) and 3.71 (sub-watershed 18).

According to Table 4, the COHESION$_L$ values obtained for all sub-watersheds are approximately between 99.50 and 99.96. SPLIT$_L$, also called effective mesh number (m_{eff}), is found at 1.95 ± 0.8 for KoozehTopraghi Watershed. This index varied from 1.01 in sub-watersheds 21 and 26 to 3.38 in sub-watershed 32. The value of DIVISION$_L$ for KoozehTopraghi Watershed was obtained at 0.39 ± 0.23 m out of one with minimal and maximal values of 0.75 m (sub-watershed 9) and 0.01 m (sub-watersheds 21 and 26), respectively. As shown in Table 4, the values for the PD$_L$ in sub-watershed 33 are greater than one, which shows the highest diversity and frequency in this sub-watershed, and sub-watershed 21 has minimal PD$_L$.

PRD as a quantitative measure of landscape composition was obtained at 0.23 ± 0.14 with minimal and maximal of 0.06 and 0.80 No. per ha for KoozehTopraghi Watershed.

It was found that the KoozehTopraghi Watershed had a mean and standard deviation of 0.57 ± 0.29 in terms of SHDI. Sub-watershed 18 with an SHDI value of 1.18, and sub-watershed 11 with a value of 0.23, were the best and worst parts of the study area in terms of fragmentation state.

MSIDI values in the study watershed ranged from 0.01 to 0.96 with a mean of 0.42 ± 0.26. According to Table 4, the values obtained for MSIDI show the high land use diversity in all sub-watersheds except 21, 25, and 26. Low diversity is due to the patches uniformity and the non-appropriate distribution of patches.

3.4. Fragmentation Hot Spots and Clustering Analysis

The summary of the classification of 36 study sub-watersheds of KoozehTopraghi at different categories of hot and cold spots and various confidence levels is provided in Figure 4 and Table 5. According to the results of the Getis-Ord Gi* statistic and its generated ZScore and p-value (Figure 4), in most study sub-watersheds, there was no significant spatial pattern. For instance, the significant cold spots of PD metric in sub-watersheds 23 and 25 were classified at a 99% confidence level. Regarding LPI, sub-watersheds 23 and 36 were classified as significant hot spots at a 99% confidence level, and sub-watersheds 34 and 17 were classified as significant cold spots at a 90% confidence level. In addition, sub-watersheds 1, 25, 26, and 27 were recognized as significant hot spots at a 95% confidence level.

Regarding AREA-MN, sub-watersheds 9, 28, 29, and 34 were classified as significant cold spots at a 90% confidence level, and sub-watersheds 23, 35, and 36 were classified as significant hot spots at a 99% confidence level. Sub-watersheds 22 and 25 were also significant hot spots at a 95% confidence level. Out of 36 study sub-watersheds, 20 cases accounted for significant hot spots at a 90% confidence level. According to the TE results, 52.5% of the whole study watershed (including sub-watersheds 23, 24, 25, 27, 30, 35, and 36) were identified as significant cold spots at a 90% confidence level, and 1.44% of the total watershed was placed in the significant cold spots category at the 95% confidence level (Table 5).

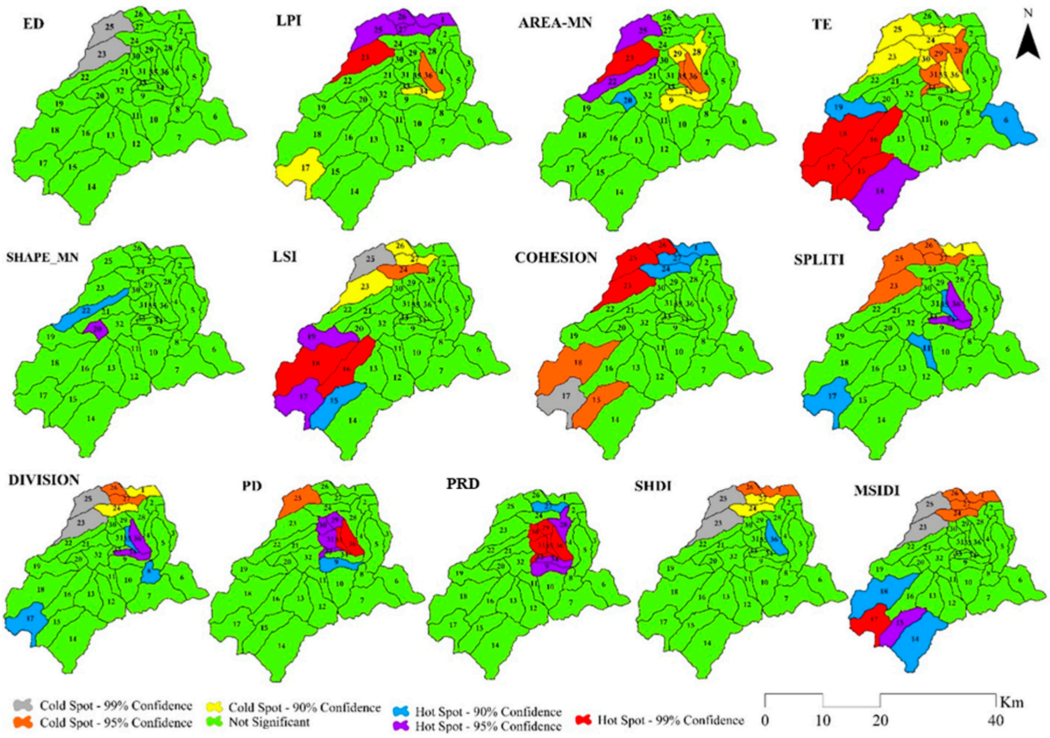


Figure 4. Spatial distribution of hot spots of fragmentation metrics in the KoozehTopraghi Watershed.

Table 5. Summary of the spatial distribution of hot spots of fragmentation metrics in the sub-watersheds of KoozehTopraghi (No. 1–36).

Metric / Classification	ED_L	LPI_L	$AREA\_MN_L$	TE_L	$SHAPE\_MN_L$	LSI_L	$COHESION_L$	$SPLIT_L$	$DIVISION_L$	PD_L	PRD	SHDI	MSIDI
Cold spot—99% Confidence	25, 23	-	-	-	-	25	17	-	23, 25	-	-	23, 25	23, 25
Area (%)	0.72	-	-	-	-	0.36	0.36	-	0.72	-	-	0.72	0.72
Cold spot—95% Confidence	-	-	-	28, 29, 31, 33	-	24	15, 18	23, 26, 26, 27	26, 27	25	-	1,26	1, 24, 26, 27
Area (%)	-	-	-	1.44		0.36	0.72	1.44	0.72	0.36		0.72	1.44
Cold spot—90% Confidence	-	17, 34	9, 28, 29, 34	24, 25, 23, 27, 30, 35, 36	-	23, 26, 27	-	1	1, 24	-	-	24, 27	-
Area (%)	-	0.72	1.44	2.52	-	1.08	-	0.36	0.72	-	-	0.72	-
Hot spot—90% Confidence	-	-	20	6, 19	22	15	1, 24, 27	11, 17, 35	8, 17, 35	9	27	36	14, 18
Area (%)	-	-	0.36	0.72	0.36	0.36	1.08	1.08	1.08	0.36	0.36	0.36	0.72
Hot spot—95% Confidence	-	1, 25, 26, 27	22, 25	14	20	17, 19	-	34, 36	36, 34	29, 30, 31, 33	28, 34, 9	-	15
Area (%)	-	1.44	0.72	0.36	0.36	0.72	-	0.72	0.72	1.44	1.08	-	0.36
Hot spot—99% Confidence	-	23, 36	23, 35, 36	15, 16, 17, 18	-	16, 18	23, 25, 26	-	-	25, 36	29, 30, 31, 33, 35, 36	-	17
Area (%)	-	0.72	1.08	1.44	-	0.72	1.08	-	-	0.72	2.16	-	0.36
Not Significant	Other sub-watersheds												
Area (%)	99.28	97.12	96.4	93.52	99.28	96.4	96.76	96.4	96.04	97.12	96.4	97.48	96.4

According to Local Moran's I results (Figure 5), most of the study sub-watersheds were recognized with no specific clustering pattern. Nevertheless, in the ED metric, sub-watersheds 23 and 25 and sub-watersheds 11 and 35 were clustered in the high and low classes, respectively. For the LPI metric, sub-watersheds 23, 25, and 26 were classified as high cluster, and sub-watershed 11 as high outlier. For the AREA-MN metric, sub-watersheds 23, 25, and 26 were classified as a high cluster, and sub-watershed 29 was classified as low outlier. For the TE metric, sub-watersheds 13, 14, 16, 17, and 18 were classified as high cluster. For the SHAPE-MN metric, sub-watershed 20 was clustered in high-class, and sub-watershed 26 was classified as a low outlier. For the LSI metric, sub-watersheds 16, 17, and 18 were classified as high cluster, and sub-watershed 25 was classified as low outlier.

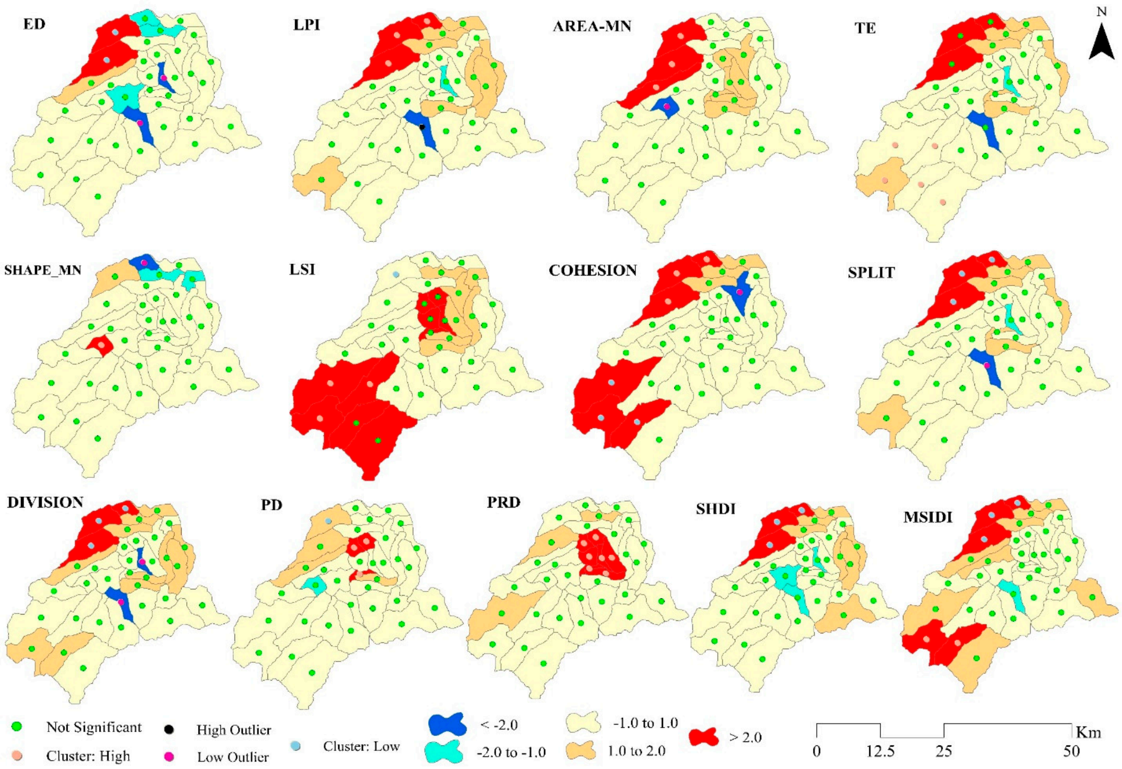


Figure 5. Clustering patterns and spatial autocorrelation of the study fragmentation metrics in the KoozehTopraghi Watershed.

For the COHESION metric, sub-watersheds 16, 17, and 18 were classified as low cluster, sub-watershed 28 was classified as low outlier, and sub-watersheds 23, 25, and 26 were classified as a high cluster class. For the SPLIT metric, sub-watersheds 23, 25, and 26 were classified in the low cluster class, and sub-watershed 11 was classified as a low outlier. For the DIVISION metric, sub-watersheds 23, 25, and 26 were classified as high cluster, and sub-watersheds 11 and 35 were classified as low outlier. For the PD metric, sub-watersheds 29, 30, and 33 were classified as a high cluster class, and sub-watershed 25 was classified as a low outlier. Regarding PRD metrics, sub-watersheds 29, 30, 31, 33, 34, 35, and 36 were classified into a high cluster class. For the SHDI metric, sub-watersheds 23, 25, and 26 were classified as low cluster as well as sub-watersheds 15 and 17 as high cluster.

4. Discussion

Fragmentation metrics at three levels of patch, class, and landscape provide easy-to-use maps of spatial distribution and informative approaches for regional sustainable land planning. Patches that characterize distinct areas with akin features are subjected to patch-level metrics. While entire patches of land use/land cover categories are used to calculate class-level metrics. Finally, landscape-level metrics are computed through a mixture of entire patch and class types in study sub-watersheds [24].

Our results about the AREA_CPS (34.33 ± 10.30%) and AREA_LPS (49.22 ± 2.41%) at patch-level study were relatively similar to the result reported by Esfandiyari Darabad et al. [34] in Gharesou River Watershed, Ardabil Province who found the AREA_CPS between 25.75 and 36.96 and AREA_LPS between 28.94 and 38.95%, indicating the relatively high fragmentation. These metrics also indicated that the sub-watersheds with the maximum value had the maximum landscape continuity. PERIM is another fundamental metric that is considered a basis for many landscape analyses. Specifically, the patch perimeter is studied as an edge length. Here, the edge's intensity and distribution establish the main characteristic of landscape configuration and pattern [23]. In addition, its connection with the patch area provided the critical basis for many shape metrics [9,24]. GYRATE is a degree of patch extent affected by patch size and compaction [24]. If the patch contains a single cell and rises without limit with increasing patch extent, it results in to GYRATE of zero. It reaches its extreme value when the patch encompasses the whole landscape as obtained for sub-watershed 21 with the value of 1624.60 m (Table 2). As the GYRATE increase, the cohesion between the patches decreases [24]. The high variability was observed for PERIM and GYRATE at a spatial scale, indicating the extreme heterogeneity in patch extent and affectability by both patch size and patch compaction.

Patches with less geometrical complexity can be observed in the managed landscape [26]. SHAPE and FRAC metrics are in a positive relationship with fragmented. Their low mean (Shape = 1.04, FRAC = 1.26) represented low fragmentation in the study watershed. However, Yuan et al. [35] observed the increase in FRAC at the Qinhuai River Basin from 2003 to 2017, emphasizing the increase in urban lands and their complexity. The CIRCLE metric was also estimated in low to medium value (0.37 ± 0.83). CIRCLE metric quantifies the overall patch elongation. Indeed, it assessed the patch shape or related circumscribing circle according to the patch area/the smallest circumscribing circle area [36].

Considering the average value of metrics as a threshold, sub-watershed 7 is recognized as the most fragmented sub-watershed in terms of all study patch-level metrics. Sub-watersheds 18 and 25 are in a critical situation in terms of five metrics. Therefore, in these watersheds, taking into account special management programs and measures should be the prime goal to functionally and structurally enhance the vegetation cover.

In terms of class-level analysis, metrics of ED_C, $SHAPE\_MN_C$, LSI_C, $SPLIT_C$, $DIVISION_C$, and PD_C are in positive relation with fragmentation, and they recorded different spatial variations (Table 3, Figure 3). The highest values of them were found in dry farming, good rangeland, orchard, residential, residential, and residential land uses. In addition, the residential land use is in the lowest value of LPI_C and EA_MN_C. ED_C, as the equivalent total length of the edge, is considered the most commonly used metric in studies quantifying the effects of fragmentation at class level [25]. LPI_C, as a simple metric of dominance, assesses the percent of total landscape area contained within the largest patch [37]. LPI_C is equal to 0 and 100 when the largest patch of the specific patch type is very small and the whole landscape entails a single patch of the corresponding patch type, respectively. With an increase in the values of LPI_C, the connection and continuity of the surface of the landscape increase. At the class level, if the patch is larger, the ED_C is greater. In this regard, Kowe et al. [3] found an increase in ED_C from 109.5 m ha^{-1} (in 1994) to 117.8 m ha^{-1} (in 2017), denoting an increasing trend in vegetation fragmentation. The high value of this metric was also found by Mohammadi and Fatemizadeh [38] in southern Iran, and its increasing trend (from 1.77 to 1.85 m ha^{-1} for rangeland) was approved due to highway construction.

Our results showed LPI_C with lower than 50 throughout all land uses of KoozehTopraghi Watershed. This shows that there are high and moderate levels of disconnectivity through the dominant land uses. In this regard, Mohammadi and Fatemizadeh [38] also found a high LPI_C for the Tang-e Bostanak Protected Area (more than 83%); however, a 0.41% decrease in LPI_C was observed after highway construction. Narmada et al. [9]

reported LPI_C ranges of 0.45–31.13, 0.98–27.69, and 2.25–18.45% for 2000, 2008, and 2019, respectively. In all study years, the highest LPI_C was obtained for the evergreen class, with an increasing trend in its fragmentation. This is inconsistent with the higher value of AREA–MN_C in moderate rangeland and dry farming, for the State of Rondônia, Brazilian Amazon. Batistella et al. [39] also found the highest AREA–MN_C in the forest (76.94–106.59 ha) followed by bareland/cropland (7.27–8.81 ha). They reported the highest and lowest TE_C in the forest (3,905,970–3,905,970 m) and water bodies (30,030–175,020 m), respectively. The LSI_C metric indicates the degree of patch irregularity. In addition, the relative importance of edge length and area of patch types is explained by LSI_C [39]. Therefore, increasing the amount of LSI_C means increasing the irregularity and class complexity in the study watershed.

$COHESION_C$ is employed to describe the class aggregation and physical connectedness of the corresponding patch type [25,40] in the subjected land uses of KoozehTopraghi Watershed. As the patches continue to increase, the value of this indicator also increases. Jaeger [41] considered the $SPLIT_C$ as a fragmentation metric for quantifying six fragmentation phases, including perforation, incision, dissection, dissipation, shrinkage, and attrition. It was found that by increasing the PD_C, the connectivity of the landscape decreases, and the patches become smaller and more regularized, as also noted by Kang et al. [16]. Therefore, the abundant presence of small patches in various vegetation coatings lead to a decrease in the intervals of two similar patches and an increasing PD_C of residential land use in the KoozehTopraghi Watershed. Then, orchard and irrigation land uses had PD_C values of 0.04 and 0.03 per ha, respectively. The rangeland land use had a lower PD_C, indicating that the cohesion and continuity in this land use are high.

At the landscape level, metrics of $AREA\_MN_L$, TE_L, $SHAPE\_MN_L$, LSI_L, $COHESION_L$, $SPLIT_L$, $DIVISION_L$, PD_L, PRD, SHDI, and MSIDI allocated more than 50% variance throughout study sub-watersheds. The ED_L has been recognized as a powerful metric representing the watershed structure (e.g., [7]), habitat loss (e.g., [42]), abundance (e.g., [6]), and spatial aggregation (e.g., [6,25]), habitat pattern and composition (e.g., [6]), and so on. At the landscape level, the relationship between ED_L and landscape fragmentation is positive [43].

The spatial pattern of LPI_L for different conditions was obtained similar to our results (e.g., [5–7,17]). Liu et al. [42] found an exponential and positive relationship with decreasing trend between Area_MN and habitat loss based on the analysis of 16 large cities around the world. In addition, Rakhmawati [44] reported a significant reduction in $AREA\_MN_L$ metric from 2001 to 2016 at Gunung Halimun Salak National Park (GHSNP) as one of the protected areas in Indonesia. The range of $Area\_MN_L$ through GHSNP was noted between 3.2 and 295.5 ha. The results verified a progressive reduction in the size of the study forests. TE_L at the landscape level is an absolute measure of the total edge length of all patch types. According to Table 4, the maximum and minimum of TE_L for KoozehTopraghi Watershed at landscape level were obtained for sub-watersheds 37 (61,383.00 m) and 21 (1338.37 m), respectively. As the TE_L increases, the landscape connectivity and cohesion decrease, and the patches become more petite and more regular, similar results were reported by Khazaei and Azari Dehkordi [45] and Kiyani and Feghhi [17] for the north of Iran.

$SHAPE\_MN_L$ is used as the representative metric of the shape complexity of landscape structure [46]. This metric varied between 1.32 (sub-watershed 25) and 2.07 (sub-watershed 21). Moreover, this metric for a square-shaped patch is equal to one. With increasing the shape irregularity, it becomes larger [17]. $SHAPE\_MN_L$ demonstrates the critical consequences of human impacts on landscapes [46]. Furthermore, LSI_L is an aggregation metric that deals with the spatial property of dispersion [43]. The LSI_L is equal to one, indicating the landscape consists of a patch with maximum compression and approximately has a square shape. When the patch is more fragmented, the boundary is more amorphous, and its shape becomes more complicated. The high correlation between LSI_L and habitat abundance and spatial aggregation was found by Wang et al. [6] in northeast Alberta, Canada. $AREA\_MN_L$ is a type of landscape metric based on the mean patch characteristic providing a measure of central tendency in the corresponding patch characteristic across the entire landscape [43]. In addition, the value of the $COHESION_L$ metric was reported by Akçakaya et al. [23] for some parts of the United States between 96.14 and 97.65. The $COHESION_L$ explains the physical connectivity of the land use patches, it is generally employed to describe the changes in landscape connectivity resulting from fragmentation in different studies (e.g., [6,40]). Uuemaa et al. [46] noted that the theoretical range of $COHESION_L$ is 0−100, but the actual range was 98−100 for Estonian landscapes. PRD metric is also used in other studies to analyze landscape fragmentation (e.g., [47] in Germany, [46] in Estonia, [48] in the Czech Republic).

According to Akçakaya [23], Jaeger [41], and McGarigal [43], $SPLIT_L$ represents the "number of patches one gets when dividing the region into parts of equal size in such a way that the new configuration leads to the same degree of landscape division". $DIVISION_L$ characterizes "the anthropogenic penetration of landscapes based on the distribution function of the remaining patch sizes" as also mentioned by Jaeger [41] and Wang et al. [6]. The presence of high PD_L in the study sub-watersheds indicates the land use degradation, which has led to fragmentation increase. It is believed that the PD_L of a particular land use type may influence critical ecological processes of the watershed. These results are inconsistent with finding by Kang et al. [16] who found that PD_L in Japan was reduced, and the urban areas, pastures, and rangelands were concentrated within the large patches. It is believed that the PD_L of a particular habitat type may affect various ecological processes, depending on the landscape context.

SHDI [49] is one of the crucial metrics frequently used to measure the diversity of the constituents of the landscape [37]. The SHDI calculates the relative variation in each patch. If there is only one patch in the landscape, then this index is equal to zero, and when the number of patches increases and the distribution of the area is proportional to the increase with the patches types, it would be equal to one [24]. The MSIDI [50,51] is selected along with SHDI as the most popular diversity index and is widely employed to quantify landscape composition [37]. MSIDI is more sensitive to the most abundant patches. When the number of the homogeneity is one, the landscape is very diverse, and when it descends to zero, the landscape diversity diminishes [24]. Therefore, the most suitable diversity and appropriate spatial patterns between different landscapes were observed in most study sub-watersheds.

Generally, the Moran index showed mainly positive values for different metrics in most sub-watersheds (Figures 4 and 5, Table 5). This indicates that the spatial distribution of the metrics is clustered. However, the correlation of the study fragmentation metrics was not high, indicating a high data concentration. Results of the Getis-Ord Gi* and Moran indices for Harare metropolitan city in Zimbabwe [3] dedicated various spatial vegetation clustering varied from dispersed to highly clustered. Hot spots of vegetation patches were also found at confidence levels of 90, 95, and 99%. Furthermore, a slight reduction in hot spots and an increase in cold spots at a 99% confidence level were obtained. The statistically significant hot spots were mainly concentrated in the northern part of Harare metropolitan city, a more vegetated area of large and contiguous vegetation patches.

The results of the present study are significant for prioritizing sub-watersheds to land management objectives. Our findings also are valuable for illustrating the spatial variation in fragmentation patterns for regional studies, as concluded by others (e.g., [12,37]). Practical analysis of fragmentation metrics affords a forthright tool for assessing the impact of future land-management projects and human activities on landscape integrity.

Regarding the limitations of the current research, it can be said that the scale dependence of some landscape metrics with spatial resolution requires special attention in choosing the appropriate scale in landscape ecology studies and the accurate interpretation of ecological processes. Therefore, calculating the landscape metrics on a suitable scale affects the identification of ecological processes, prediction of ecological functions (landscape modeling), and the reduction in uncertainty. By increasing the spatial resolution (smaller cell size), the difference in the behavior of the gauges is better understood. The weighting and selection of more effective landscape metrics in ecological processes is influenced by the views of experts and the study objectives. Therefore, the selection of the panel members in an expert elicitation procedure with a comprehensive view on landscape ecology and ecological processes and their potential impacts on different landscape changes is strongly recommended. Moreover, emphasizing the selection of metrics that better interpret change processes is important, and in this regard, focusing on composition (amount) and configuration (i.e., connectivity) provides more details and a better understanding of the landscape analysis.

Considering all factors affecting the spatial pattern of clusters and analyzing hot spots is also another research limitation. In other words, it is difficult and complex to incorporate all the driving forces affecting the change and fragmentation of the landscape, such as population, climate, human activities, and the cumulative effect of land degradation. It is possible to understand changes in landscape patterns under different management conditions by combining spatial and temporal analysis of different criteria, but the limitations caused by changes in land management, as well as climatic and physical conditions, should also be taken into account.

5. Conclusions

Spatial patterns of fragmentation metrics for quantifying environmental change are supported by landscape ecology research. Three levels of patch, class, and landscape metrics were separately widely used to assess the degree and spatial dynamics of landscape fragmentation. These different levels of landscape metrics also contain different natures of shape, patch, and isolation and are applied for detecting structural and functional aspects of vegetation cover. The present study provides an integrated and comprehensive analysis of all landscape metrics in the three levels simultaneously. At the same time, their clustering patterns and spatial autocorrelation were also investigated. Such multilateral analysis, which obtains less attention by researchers, provides a road map for land managers and decisionmakers at local, regional, national, and international levels to reach reliable monitoring tools to change detection in land cover and use, particularly from the arid and semi-arid areas. This study was planned for the KoozehTopraghi Watershed, NW Iran, as a case study located in cold semi-arid parts. To this end, land use datasets were provided to derive or calculate fragmentation metrics. As a result, the following patterns of the land fragmentation metrics through 36 study sub-watersheds should be noted:

- A high spatial variation was found between different study fragmentation metrics;
- At the patch level, most watersheds are in a moderate or critical state regarding AREA_CPS, AREA_LPS, SHAPE, FRAC, and CIRCLE metrics. About 50% of the watershed is under the average state regarding AREA_CPS, PERIM, and GYRATE metrics. Therefore, it is imperative to develop effective conservation strategies in the critical sub-watersheds;
- At the class level, the most and least fragmented land use was mainly allocated to residential and dry farming land uses, respectively. It can be concluded that although the residential land use comprises only 0.75% of the study watershed, residential land use needs more management attention because it leads to the most degradation and threats in the watershed;
- At the landscape level, sub-watersheds 1, 2, 11, 21, to 26, and 34 to 36 obtained the better status of the study fragmentation metrics and had a better general situation than other parts of the watershed. These sub-watersheds are located in regions with less than 1732 m elevations and are almost covered by dry farming land use. The present results show the hot and cold spots for future consideration of the design features and best management practices.

The prominent target organizations in Iran (e.g., Department of Environment, Natural Resources and Watershed Management Organization, and Research Institute of Forests and Rangelands) as well as at the international level (e.g., Convention on Biological Diversity, the European Biodiversity Observation Network, and the Biodiversity Indicators Partnership) can apply and implement the informative results of the present research in different subjects such as land use planning, process-based interactions modeling, environmental impact assessments, natural resources management, rural development, and biodiversity conservation for national and international contexts.

For future research, since KoozehTopraghi Watershed has been under urban and agriculture development pressure during the last two decades, analysis of the temporal variation in the fragmentation metrics on a long-term scale, which is important for conservation purposes, is suggested. In addition, using novel fragmentation metrics and comparing their results with the present study complements and supplements the analysis of land fragmentation. Providing a core set of best and adaptive management and conservation practices to reduce the landscape fragmentation impacts should be performed by future research.

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Appendix A

Table A1. Selected metrics at patch level for fragmentation analysis of the KoozehTopraghi Watershed, Ardabil Province, Iran.

Metrics Name (Its +/− Relation with Fragmentation)	Description	Symbol	Formula	Value Range	Units
Percentile of the class distribution (−)	"These metrics are obtained by rank ordering observations from lowest to highest and computing the percentage of observations smaller than the observed value for the focal patch."	AREA_CPS	$CPS = \left(\frac{rank(X_{ij})-1}{n_i-1}\right)(100)$	$0 \leq \text{metric} \leq 100$	%
Percentile of the landscape distribution (−)		AREA_LPS	$LPS = \left(\frac{rank(X_{ij})-1}{N-1}\right)(100)$	$0 \leq \text{metric} \leq 100$	%
Perimeter (−)	"This metric indicated the perimeter of patch, including internal holes, regardless of whether perimeter represents true edge or not."	PERIM	$\text{PERIM} = p_{ij}$	PERIM > 0, without limit	m
Radius of gyration (−)	"The measure of patch extent; that is, how far across the landscape a patch extends its reach. All other things equal, the larger the patch, the larger the radius of gyration."	GYRATE	$\text{GYRATE} = \sum_{r=1}^{z} \frac{h_{ijr}}{z}$	$\text{GYRATE} \geq 0$, without limit	m
Shape index (+)	"This index measures the complexity of patch shape compared to a standard shape (square) of the same size."	SHAPE	$\text{SHAPE} = \frac{0/25P_{ij}}{\sqrt{a_{ij}}}$	$\text{SHAPE} \geq 1$, without limit	-

Table A1. *Cont.*

Metrics Name (Its +/− Relation with Fragmentation)	Description	Symbol	Formula	Value Range	Units
Fractal dimension index (+)	"It reflects shape complexity across range of patch sizes."	FRAC	$\mathrm{FRAC} = \frac{2\ln(0/25p_{ij})}{\ln a_{ij}}$	$1 \leq \mathrm{FRAC} \leq 2$	-
Related circumscribing circle (−)	"Index to compare the area of the patch to the area of the smallest circle that can circumscribe the patch."	CIRCLE	$\mathrm{CIRCLE} = 1 - \left[\frac{a_{ij}}{a_{ij}^{s}}\right]$	$0 < \mathrm{CIRCLE} < 1$	-

x_{ij}: value of a patch metric for patch ij; n_i: number of patches of the corresponding patch type (class) II; N: number of patches in the landscape; p_{ij}: perimeter (m) of patch ij; h_{ijr}: distance (m) between cell ijr (located within patch ij) and the centroid of patch ij (the average location), based on cell center-to-cell center distance; z: number of cells in patch ij; a_{ij}: area (m^2) of patch ij; and $a_{ij}{}^{s}$: area (m^2) of the smallest circumscribing circle around patch ij (derived from [22,24–26].

Table A2. Selected metrics at class level for fragmentation analysis of the KoozehTopraghi Watershed, Ardabil Province, Iran.

Metrics Name (Its +/− Relation with Fragmentation)	Description	Symbol	Formula	Value Range	Units
Edge density (+)	"It standardizes edge to a per unit area basis."	$\mathrm{ED_C}$	$\mathrm{ED} = \frac{\sum_{k=1}^{m} e_{ik}}{A}(10{,}000)$	$\mathrm{ED} \geq 0$, without limit	$\mathrm{m\ ha^{-1}}$
Largest patch index (−)	"The percentage of the landscape comprised by the largest patch of the corresponding patch type (class level)."	$\mathrm{LPI_C}$	$\frac{\max_{j=1}^{n} a_{ij}}{A}(100)$	$0 < \mathrm{LPI} \leqq 100$	%
Mean patch area (−)	"Average area of a patch for a particular class of land cover."	$\mathrm{AREA\_MN_C}$	$\mathrm{AREA - MN} = a_{ij}\frac{1}{10{,}000}$	$\mathrm{AREA} > 0$	ha
Total edge (−)	"Total edge is an absolute measure of total edge length of a particular patch type."	$\mathrm{TE_C}$	$\sum_{k=1}^{m} e_{ik}$	$\mathrm{TE} \geq 0$, without limit.	m
Mean patch shape index (+)	"Patch perimeter divided by the minimum perimeter possible for a maximally compact patch."	$\mathrm{SHAPE\_MN_C}$	$\mathrm{SHAPE} = \frac{P_{ij}}{min P_{ij}}$	$\mathrm{SHAPE} \geq 1$	-
Landscape shape index (+)	"A standardized measure of the total edge or edge density that adjusts for the size of the landscape."	$\mathrm{LSI_C}$	$\mathrm{LSI} = \frac{0/25\sum_{k=1}^{m} e_{ik}^{*}}{\sqrt{A}}$	$\mathrm{LSI} \geq 1$, without limit	-
Patch cohesion index (−)	"It Indicates the physical connectedness of the corresponding patch type"	$\mathrm{COHESION_C}$	$\mathrm{COHESION} = \left[1 - \frac{\sum_{j=1}^{n} p_{ij}^{*}}{\sum_{j=1}^{n} p_{ij}^{*}\sqrt{p_{ij}^{*}}}\right]\left[1 - \frac{1}{\sqrt{Z}}\right]^{-1}.(100)$	$0 < \mathrm{COHESION} < 100$	-
Splitting index (+)	"Number of patches one gets when dividing the region into parts of equal size in such a way that the new configuration leads to the same degree of landscape division."	$\mathrm{SPLIT_C}$	$\mathrm{SPLIT} = \frac{A^2}{\sum_{j=1}^{n} a_{ij}^{2}}$	$1 \leq \mathrm{SPLIT} \leq$ number of cells in the landscape area squared	-
Landscape division index (+)	"Probability that two randomly chosen places in a landscape are not situated in the same un-dissected area."	$\mathrm{DIVISION_C}$	$DIVISION = \left[1 - \sum_{j=1}^{n}\left(\frac{a_{ij}}{A}\right)^{2}\right]$	$0 \leq \mathrm{DIVISION} \leq 1$	ha
Patch density (+)	"Number of patches per unit area."	$\mathrm{PD_C}$	$PD = \frac{n_i}{A}(10{,}000)(100)$	$\mathrm{PD} > 0$, constrained by cell size	Number per 100 ha

e_{ik}: total length (m) of edge in landscape involving patch type (class) i, includes landscape boundary and background segments involving patch type i; A: total landscape area (m^2); a_{ij}: area (m^2) of patch ij; $p_{ij}{}^{*}$: perimeter of patch ij in terms of number of cell surfaces; $a_{ij}{}^{*}$: area of patch ij in terms of number of cells; Z: total number of cells in the landscape; and n_i: number of patches in the landscape of patch type (class) i (derived from [22,24–26]).

Table A3. Selected metrics at landscape level for fragmentation analysis of the KoozehTopraghi Watershed, Ardabil Province, Iran.

Metrics Name (Its +/− Relation with Fragmentation)	Description	Symbol	Formula	Value Range	Units
Edge density (+)	"It equals the sum of the lengths of all edge segments in the landscape, divided by the total landscape area."	ED_L	$ED = \frac{E}{A}(10,000)$	$ED \geq 0$, without limit	m ha^{-1}
Largest patch index (−)	"It equals the sum of the lengths of all edge segments involving the corresponding patch type, divided by the total landscape area."	LPI_L	$LPI = \frac{\max(a_{ij})}{A}(100)$	$0 < LPI \leqq 100$	%
Mean patch area (−)	"This metric calculates the shortest distance between a patch and another patch of a similar type."	AREA $\_MN_L$	$AREA - MN = \sum_{j=1}^{n} a_{ij} \frac{1}{10,000}$	AREA >0	ha
Total edge (+)	"It is an absolute measure of the total edge length of all patch types."	TE_L	$TE = E$	$TE \geq 0$, without limit	m
Mean patch shape index (+)	"Patch perimeter is divided by the minimum perimeter possible for a maximally compact patch."	SHAPE $\_MN_L$	$SHAPE = \sum_{j=1}^{m} \frac{P_{ij}}{minP_{ij}}$	$SHAPE \geq 1$	-
Landscape shape index (+)	"It is a standardized measure of the total edges or the total edge density that adjusts to the size of the landscape."	LSI_L	$LSI = \frac{0/25E^*}{\sqrt{A}}$	$LSI \geq 1$, without limit	-
Patch cohesion index (−)	"It Indicates the physical connectedness of the corresponding patch type. It standardizes richness to a per-area basis that facilitates comparison among landscapes, although it does not correct for this interaction with scale."	COHE $SION_L$	$COHESION = \left[1 - \frac{\sum_{i=1}^{m}\sum_{j=1}^{m} p_{ij}}{\sum_{i=1}^{m}\sum_{j=1}^{m} p_{ij}\sqrt{a_{ij}}}\right]\left[1 - \frac{1}{\sqrt{z}}\right]^{-1}.(100)$	The behavior of this metric at the landscape level has not yet been evaluated.	-
Splitting index (+)	"It is defined as the number of patches one gets when dividing the entire landscape into patches of equal size in such a way that this new configuration leads to the same degree of landscape division as obtained for the observed cumulative area distribution."	$SPLIT_L$	$SPLIT = \frac{A^2}{\sum_{j=1}^{m}\sum_{j=1}^{n} a_{ij}^2}$	$1 \leqq SPLIT \leqq$ number of cells in the landscape area squared	-
Landscape division index (+)	"This metric is based on the cumulative patch area distribution and is interpreted as the probability that two randomly chosen pixels in the landscape are not situated in the same patch"	DIVISI ON_L	$DIVISION = \left[1 - \sum_{i=1}^{m}\sum_{j=1}^{n}\left(\frac{a_{ij}}{A}\right)^2\right]$	$0 \leqq DIVISION \leqq 1$	ha
Patch density (+)	"This metric is used to evaluate the degree and dynamics of landscape fragmentation."	PD_L	$PD = \frac{N}{A}(10,000)(100)$	PD > 0, constrained by cell size	Number per 100 ha
Patch richness density (−)	"It measures the number of patch types present."	PRD	$PD = \frac{m}{A}(10,000)(100)$	PRD > 0, without limit	Number per 100 ha
Shannon's diversity index (+)	"Based on information theory, indicates the patch diversity in a landscape."	SHDI	$SHDI = -\sum_{i=1}^{m}(p_i^* \ln p_i)$	$SHDI \geq 0$, without limit	-
Modified Simpson's diversity index (+)	"MSIDI eliminates the intuitive interpretation of Simpson's diversity index (SIDI). Diversity measure, which equals minus the ln of the sum of the squared proportional abundance of each patch type."	MSIDI	$MSIDI = -\ln \sum_{i=1}^{m} p_i^2$	$MSIDI \geq 0$, without limit	-

E: total length (m) of edge in the landscape; E*: total length (m) of edge in the landscape, includes the entire landscape boundary and some or all background edge segments; N: total number of patches in the landscape; m: number of patch types (classes) present in the landscape, excluding the landscape border if present; and P_i: proportion of the landscape occupied by patch type (class) i. Other variables are similar to Tables A1 and A2 descriptions (derived from [22,24–26]).

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