A New Combined Index to Assess the Fragmentation Status of a Forest Patch Based on Its Size, Shape Complexity, and Isolation

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Abstract: There are many local fragmentation metrics, but most can be grouped into four types (composition/area, isolation, edge, and shape), and none of them alone determines the degree of fragmentation of a patch. Here, we grouped together the main fragmentation metrics (area, edge, shape, and isolation) in order to propose a new metric/index, the Patch Fragmentation Index (PFI), with which to determine fragmentation at patch scale. The index was subsequently verified with the Ecuadorian seasonal dry forest by employing geographic information layers and temporal land uses changes in 1990, 2000, 2008, and 2018. The PFI was applied to calculate the fragmentation per patch, spatial and temporal changes of fragmentation based on PFI were assessed, and the spatial patterns (Getis-Ord Gi* analysis) were calculated. The Ecuadorian seasonal dry forest obtained a mean PFI value of 0.88 (median = 0.99) in 2018. This value has increased by 8.6% since 1990, and 3451 patches of forest disappeared between 1990 and 2018. The Getis-Ord Gi* analysis was effective with regard to describing the spatial patterns, and 62% of the patches that were classified as hot patches in 1990 had disappeared by 2018. The PFI has proven to be a useful tool with which to describe fragmentation patterns at patch scale (regardless of its size) and can be extrapolated to other landscapes. The PFI will provide a new vision and can help in the decision-making related to the conservation and management of fragmented ecosystems.

Keywords: fragmentation metric; dry forests; landscape; conservation; deforestation; fragmentation patterns

1. Introduction

International organizations such as the Convention on Biological Diversity [1], the European Biodiversity Observation Network [2], and the Biodiversity Indicators Partnership [3] have recommended the analysis of the conservation status of ecosystems through the use of fragmentation indices. Briefly, habitat fragmentation results from the dissection of contiguous habitat areas into smaller, isolated patches of various sizes and shapes, with a larger edge length exposed to the matrix [4]. Habitat fragmentation is a continuous and progressive process that reduces the areas of intact habitat cover, increases habitat edges, and isolates the remaining patches in the landscape [5]. Although it has also been defined as a process that must be separated from the loss of habitats, the two are closely linked, since fragmentation is a complex pattern and not a simple process, and is frequently related to deforestation processes [6].

Habitat loss and the subsequent fragmentation results in a wide variety of ecological, environmental, social, and economic impacts [7], and is one of the major components of global change [8]. Fragmentation has been classified as one of the main threats to tropical forests and their associated biodiversity [9,10], and has been strongly associated with the loss of species [11]. It is for these reasons that estimating habitat fragmentation is a relevant
issue in present-day ecology [12]. There are many metrics with which to calculate fragmentation, with area metrics and isolation/proximity metrics being those most commonly used in the literature on fragmentation, accounting for 48% and 42.4%, respectively [13]. However, others metrics, such as edge, shape, or patch density, are also well studied [13]. In this respect, various authors have attempted to identify the most suitable metrics for fragmentation assessment on forest patch and landscape scales [14,15]. Others metrics are oriented toward describing the formation of new edges [16,17], patch size [18,19], or degree of isolation [7,17,20]. Fragmentation studies are, therefore, shifting from patch scale to landscape scale [13], because many fragmentation effects do not depend solely on one single fragmentation metric at patch level, but rather on several at the landscape level. In fact, Fahrig (2019) [21] suggested that patch metrics cannot be extrapolated to the landscape level, suggesting that fragmentation is a landscape level process that must be studied through the use of spatial patterns. It has also been suggested that the loss of habitat and fragmentation occur at the same time, and, therefore, that their independent effects cannot be demonstrated (see, for example, Didham et al. [21]). Other authors [22,23], however, argue that the effects of fragmentation are not always negative, highlighting the importance of small patches with regard to maintaining biodiversity and the connectivity of ecosystems [24,25], as well as the fact that many smaller habitat patches may be richer in species than a few large ones [23,26]. Indeed, the “habitat amount hypothesis” suggests that the quantity of habitat in the landscape may be more important than patch size and isolation [27,28].

The calculation and interpretation of fragmentation are, consequently, subjects of debate for all of the aforementioned reasons [22,29,30], thus opening up a range of possibilities for researchers. There are many patch fragmentation metrics, but none of them alone explains or identifies the fragmentation status of a patch. The most common metrics identified and calculated in patch fragmentation are area (patch size), edge (perimeter of the patch), shape (mean patch fractal dimension-MPFD, shape index, or area/perimeter), proximity to other patches (distance to the closest patch, distance to the furthest, or average distance to other patches), or core areas [31,32]. However, these patch metrics may be misleading when they are extrapolated to the landscape [27,30,33]. Integrating the main fragmentation metrics (size, isolation, edge, and shape) into a single formula would, therefore, improve the assessment of patch fragmentation, thus making it a suitable tool for decision-making. Once the patch fragmentation has been assessed and the patches have been spatially located, their temporal and spatial evolution (e.g., increased, decreased, or stationary state) could be monitored and analyzed at landscape scale [14].

Our general objective was, therefore, to propose and interpret the ecological meaning of a new fragmentation metric, denominated as the patch fragmentation index (PFI), at patch scale, and to validate it in a highly fragmented ecosystem: the seasonal dry forest in Ecuador. The specific objectives were: (i) to analyze the efficiency of the PFI as an indicator of habitat fragmentation at patch scale; (ii) to interpret whether the PFI is useful with regard to monitoring the evolution of fragmentation at different scales (from patch to landscape); and (iii) to assess the usefulness of the PFI as an indicator of zonal fragmentation, which could provide a new research tool for decision-making in the field of forest fragmentation. The intention of this was to provide a useful tool with which to measure fragmentation that would make it possible to identify patches or areas with a good or bad state of fragmentation, in order to take effective measures in the conservation or study of patterns and causes of fragmentation.

2. Materials and Methods
2.1. Study Area

The study area selected was the seasonal dry forest in the coastal region of Ecuador (Figure 1), which is part of the Chocó–Darien–Western Ecuador, one of the world biodiversity hotspots [34]. It is a highly fragmented ecosystem [35], and despite having a worrisome conservation status, is less protected than humid forests [36]. The seasonal dry forest it is
characterized by a deciduous and semi-deciduous phenology: in deciduous forests, more than 75% of the individuals of tree or shrub species lose their leaves, and the dry periods last between six to eight months, while in semi-deciduous forests, between 25% and 75% of the individuals of tree or shrub species lose their leaves, and the dry periods last from one to six months [37,38].

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Figure 1. (A) Map of mainland Ecuador and its three geographical regions. (B) Map showing the seasonal dry forest (blue) on the equatorial coast (grey).

2.2. Dry Forest Characterization

In order to characterize the potential extent of the seasonal dry forests, the geo-referenced layers of phenology, land use, flood regime, and bioclimate were obtained from the Ecuadorian Ministry of the Environment, available at http://ide.ambiente.gob.ec/mapainteractivo accessed on 1 November 2021. All of the layers were made by the Ministry of the Environment of Ecuador. The phenology layer measured the relative and effective availability of the annual amount of precipitation in relation to average temperatures [39], and the flood regime was determined according to the saturation capacity of the soil to retain water [40]. Bioclimate refers to the interrelation between temperature, precipitation, evaporation at regional scales, and their correspondence with different types of vegetation [41]. The layer of land uses were made using Landsat satellite images and the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER); orthorectification has later been certified by experts and by means of fieldwork, with a pixel size of 30 m [42–44]. The Kappa index is approximately 0.7 [43].

The seasonal dry forest areas were then selected as those catalogued as native forest in the land use layer, which are intercepted with the deciduous and semi-deciduous phenology, while floodable areas (mangrove areas) and areas of desert bioclimate were eliminated, since these are areas of bush or desert.

2.3. Fragmentation Metrics

The most common metrics used to calculate patch fragmentation [31,32] are those related to area (patch size or patch area), edge (perimeter of the patch), shape (MPFD, shape index or area/perimeter), proximity to other patches (distance to the closest patch), or core areas. The Patch Fragmentation Index (PFI), which is based on integrating certain variables that measure the main effects of fragmentation (loss of habitat, patch size), shape
complexity (mean patch fractal dimension (MPFD)), and isolation (area of influence) into a single formula, was calculated as (Equation (1)):

\[
PFI = \frac{4}{5} \times \left(1 - \frac{Ap}{Ai}\right) + \frac{1}{5} \times \left(\frac{MPFD}{2}\right)
\]

where \( Ap = \) patch area, \( Ai = \) area of influence, \( MPFD = \) complexity of shape, and \( PFI = \) patch metric with values between 0 and 1. The closer the result is to zero, the less fragmentation there is.

The area of influence (AI) is based on the maximum area that the patch could occupy if it had not undergone deforestation processes. The \( (Ap/Ai) \) section was given a greater weight (4/5) because this section accumulates the worst effects with regard to biodiversity (habitat loss and isolation [11]) and encompasses more metrics than the MPFD section (1/5), which is divided by 2 because it is a value between 1 and 2 [45], while PFI has values of between 0 and 1. In practice, the maximum PFI value of 1 is never reached, as this signifies the disappearance of the patch and, therefore, it has neither area nor shape. Likewise, the minimum value of 0 is never reached, as the patch is always distant from others and has a shape (Figure A1).

The PFI was used to calculate the state of the Ecuadorian seasonal dry forest in 1990. For a better representation, the PFI was used as the basis on which to classify the forest patches into five categories: very high (PFI \( \geq 0.8 \)), high (0.6 \( \leq PFI \leq 0.79 \)), medium (0.4 \( \leq PFI \leq 0.59 \)), low (0.39 \( \leq PFI \leq 0.2 \)), and very low (PFI \( \leq 0.2 \)). Areas of influence (AI) were calculated by creating Voronoi areas with the forest patches that existed in 1990, which were intersected with areas of seasonal dry forest habitat in order to delimit the zone of possible growth of the seasonal dry forest. Voronoi areas were made with Graphpad Software [46], then intersected with the study area so that each Voronoi area was adjusted to the landscape.

The PFI was also used to measure temporal change. The areas of influence (AI) created for the seasonal dry forest in 1990 were then used to calculate the PFI for the years 1990, 2000, 2008, and 2018, converting the seasonal dry forest into a raster of 100 m of spatial resolution in order to delimit native forest patches. A value of PFI = 1 was given to the areas of influence in which the patches disappeared in the years 2000, 2008, and 2018 (the maximum fragmentation rate is considered if a patch has disappeared). In the areas of influence in which the number of patches increased (in the years 2000, 2008, and 2018), the new patches were considered as part of the original in 1990. This increase in the number of patches may result from reforestation or from large patches being divided.

2.4. Temporal Change in Fragmentation Based on PFI with Hexagon Grid and Areas of Influence

Two zoning temporal changes in fragmentation were calculated: first, the area of influence of the patches was used to divide the study area into smaller areas, which was carried out by giving the PFI value for the patch to the area of influence. Second, the surface was tested in a grid of hexagons of 10 km\(^2\), in which each hexagon (tile) had the average PFI of the patches that were inside. Only those hexagons with at least one forest patch inside were considered. The two analyses were carried out separately for the years 1990, 2000, 2008, and 2018.

2.5. Fragmentation Spatial Patterns

An analysis of the Gi * of Getis-Ord [47,48] was used to analyze fragmentation spatial patterns of the PFI at the patch level (see Rivas et al. [35] for more details), in which the areas of influence of the patches were used (see previous section) and a transition matrix was created, showing the status of the patches in 1990 and 2018 along with their change in status. The resulting Z-scores and P-values indicate where features with high or low values are spatially clustered [47,48]. At 5% significance (\( p \leq 0.05 \)), a Z-score greater than 1.96 indicates a hot spot, while a Z-score smaller than −1.96 indicates a cold spot, and the
remaining values are classified as not significant ($-1.96 < Z < 1.96; p > 0.05$). This tool works by searching for each entity within the context of neighboring entities.

3. Results
3.1. Fragmentation Metrics

Figure 2 shows the patches of seasonal dry forest in the coastal region of Ecuador in 1990, categorized according to their PFI value. Highly fragmented areas spatially coexist with less fragmented areas, showing how the PFI classifies each patch on the basis of its state of fragmentation.

![Figure 2](image)

Figure 2. Degree of fragmentation of the seasonal dry forest in Ecuador in 1990 (left) using the PFI. The figures in details (A–F) show the state of fragmentation of the patches and their area of influence (black lines): (PFI $\geq 0.8$), high (0.6 $\leq$ PFI $\leq$ 0.79), medium (0.4 $\leq$ PFI $\leq$ 0.59), low (0.39 $\leq$ PFI $\leq$ 0.2), and very low (PFI $\leq$ 0.2).

Fragmentation per patch increased during the study period, with a higher mean PFI value in 2018 (0.88) than in 1990 (0.81) (Table 1), increasing by 8.6% in this period. Moreover, 3451 patches had disappeared since 1990. There were 6908 patches in 1990, of which only 3457 remained in 2018, signifying that almost half of the patches had been deforested since 1990 (Figure 3, Table 1). PFI was also measured in different years to monitor the temporal changes of certain patches with different features. For example, the evolution of the central patch (patch inside blue squares), the largest in the landscape, has higher fragmentation despite the fact that it is larger than other surrounding patches (Figure 3). Furthermore, Figure 3 shows an area in which many patches have disappeared, signifying that the fragmentation status of the landscape has worsened (Figure 3).

3.2. Temporal Change in Fragmentation Based on PFI with Hexagon Grid and Areas of Influence

In the study area, 3457 areas of influence have lost their patches of forest. These were located mainly in the north-central and the eastern and western zones (Figure 4). The homogeneous zoning based on the hexagons grid remained more similar over time, with a lower mean value than the zoning by the area of influence (Figure 5, Table 2). In 2018, there were 25% fewer homogeneous zones than with the zoning by the area of influence, and 350 hexagons lost all their forest patches between 1990 and 2018.
Table 1. Temporal evolution of the mean and median value of PFI measured at the patch level. The number of deforested patches indicates those deforested patches between 1990 and the indicated year. S.D. = standard deviation.

| Descriptive Statistics | 1990  | 2000  | 2008  | 2018  |
|------------------------|-------|-------|-------|-------|
| N°. deforested patches | 0     | 2481  | 3348  | 3451  |
| Mean                   | 0.81  | 0.85  | 0.87  | 0.88  |
| Median                 | 0.85  | 0.90  | 0.92  | 0.99  |
| S.D                    | 0.09  | 0.13  | 0.13  | 0.12  |

Figure 3. Evolution of the fragmentation degree of the seasonal dry forest in Ecuador from 1990 to 2018 using PFI. (A, B) show some areas in detail. PFI value: (PFI ≤ 0.2), and very low (PFI ≤ 0.2). Areas of influence that lost their forest patches were considered deforested.

Figure 4. Evolution of the state of fragmentation using the PFI and the area of influence as delimitation (PFI ≥ 0.8), high (0.6 ≤ PFI ≤ 0.79), medium (0.4 ≤ PFI ≤ 0.59), low (0.39 ≤ PFI ≤ 0.2), and very low (PFI ≤ 0.2). Areas of influence that lost their forest patches were considered deforested.
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Figure 5. Evolution of fragmentation status using PFI and a homogeneous tessellation by hexagons of 10 km$^2$. PFI value: very high (PFI $\geq 0.8$), high (0.6 $\leq$ PFI $\leq$ 0.79), medium (0.4 $\leq$ PFI $\leq$ 0.59), low (0.39 $\leq$ PFI $\leq$ 0.2), and very low (PFI $\leq$ 0.2).

Table 2. Evolution of mean and median value of PFI in a homogeneous zoning. The number of hexagons indicates the number of hexagons with at least one forest patch. S.D. = standard deviation.

| Year   | 1990 | 2000 | 2008 | 2018 |
|--------|------|------|------|------|
| N°. of hexagons | 3091 | 2919 | 2681 | 2741 |
| Mean   | 0.67 | 0.63 | 0.62 | 0.66 |
| Median | 0.73 | 0.65 | 0.63 | 0.69 |
| S.D    | 0.16 | 0.17 | 0.15 | 0.15 |

3.3. Fragmentation Spatial Patterns

With regard to the analysis of hot spots (Gi * of Getis-Ord), the PFI was very efficient with regard to identifying patches and areas at risk of becoming more fragmented or disappearing (Figure 6), as 1808 (62.9%) patches defined as fragmentation hot spots in 1990 had disappeared by 2018 (Table 3). However, 1138 patches classified as not significant in 1990 had also disappeared by 2018 (Table 3).

Table 3. Hot spot change matrix showing the number of patches that changed from one to another status from 1990 to 2018. NS = not significant change.

|        | 1990 | 2000 | 2008 | 2018 |
|--------|------|------|------|------|
|        | Cold | NS   | Hot  | Deforested | Total |
| 1990   | Cold | 879  | 314  | 22    | 505   | 1720  |
|        | NS   | 139  | 634  | 403   | 1138  | 2314  |
|        | Hot  | 19   | 228  | 819   | 1808  | 2874  |
| Total  | 1037 | 1176 | 1244 | 3451  | 6908  |
had disappeared by 2018 (Table 3). However, 1138 patches classified as not significant in 1990 had also disappeared by 2018 (Table 3).

Figure 6. Analysis of seasonal dry forest hotspots in 1990 and 2018 based on the PFI extended to the area of influence, in which a significant number of hotspots identified in 1990 have disappeared by 2018. Figures in detail, (A–D), showed areas of hot spots identified in 1990 that have disappeared in 2018. The Voronoi white areas in 2018 represent the patches that disappeared during the study period.

4. Discussion

Fragmentation patterns have been studied for more than 30 years. These studies have been conducted using multiple metrics, which can be sorted into several groups [49–51] in order to reduce redundancies in the calculation and distortion of fragmentation [50]. As shown by Chen et al. [51], only four types of metrics explain 89% of the variation of fragmentation metrics. These four metrics are, in order of importance: composition and area, isolation, edge (e.g., the third would be a combination of the first and second), and shape. For their part, Rogan and Lacher [8] considered that these four metrics reflect the main alterations in habitat (the habitat matrix metric has been excluded because it refers to human-modified land that surrounds or intersperses remnant native habitat patches in fragmented landscapes [11]), and have been shown to be useful with regard to describing detrimental effects on plant and animal species. The Patch Fragmentation Index (PFI) proposed in this work is, therefore, a useful and accurate tool with which to measure the patch fragmentation status, because it represents the four key metrics.

4.1. Fragmentation Metrics

One of the metrics most frequently used in fragmentation is the area of the patch, since it indicates a small amount of habitat and greater proximity to the edge. Area effect is related to the size of the patch, in which resources become limited when it decreases, thus reducing the population size and also affecting reproductive success and colonization rates [52]. If these mechanisms work together, vortices can be produced, putting populations at greater risk of extinction [8]. When considering the shape of a habitat patch, there is a higher level of edge in relation to the area [8]. Complex-shaped patches can be more easily divided into smaller patches, thus exposing the central habitat and increasing fragmentation [53]. Moreover, more complex shapes can increase the degree to which the edge of the patch infringes on the central habitat of the patch, thus reducing the amount of central habitat available for occupation by forest-interior specialists [8,54]. The mean patch fractal dimension (MPFD) is a measure of the complexity of the shape, which is close to one for shapes with simple perimeters (such as circles or squares), and close to two when the shapes are more complex [45]. The complexity of the shape is related to fragmentation
because there is more edge in relation to the area of the patch in more complex shapes, thus increasing the edge effect, which has been shown to have detrimental effects on fauna and flora. Nevertheless, edge effects can increase biodiversity at the edges of the patch, because species that live in the matrix or in surrounding areas might colonize that patch; however, patch habitat and forest-interior specialists are affected [8]. The lack of connectivity as a result of patch isolation has been linked to a reduction in movement among forest fragments, thus reducing fragment recolonization after local extinction [55]. Connectivity tends to decrease or even be completely lost as a result of fragmentation and land use change, which are produced mainly by anthropogenic activities [56].

The PFI includes the fundamental fragmentation processes, such as the formation of new edges (the MPFD is a shape metric), smaller patches (area of the patch), or more isolated patches (area of influence), signifying that the metric encompasses several aspects, thus making it more complete and indicative of the state of the patch.

4.2. Fragmentation of Seasonal Dry Forest in Ecuador

Fragmentation is a process that must be monitored for effective forest management. Monitoring helps to highlight those areas of rapid change that require the attention of conservation professionals and forest managers on the ground, and it also helps researchers to understand direct and indirect socio-economic drivers of loss [57]. Changes in fragmentation at the patch scale (increasing, decreasing, or maintaining) cannot be assessed if certain measures for different times are not available, which is why the temporal evolution of fragmentation is very useful with regard to making decisions and identifying the causes and consequences of fragmentation.

Our results showed high fragmentation levels of the Ecuadorian seasonal dry forest, as has already been demonstrated previously, using different methodologies [35,58]. The PFI value was close to 1 in 2018, which showed an increase of 22% since 1990, indicating that the majority of patches have a high degree of fragmentation or have already disappeared. When using conventional fragmentation metrics, it is possible to find the errors that are summarized and discussed in Table 4, but these do not occur when using the PFI. The PFI metric has also proven to be efficient when establishing fragmentation zones using the area of influence of the patches. Some authors have classified the landscape using geometric figures such as squares (raster) or hexagons [14,25]. The hexagon has been shown to be more efficient [59], although it has drawbacks, as shown in Figure 7A. These include islands that are smaller than the tessellation, a mix with other ecosystems, other ecosystems within the study area, littoral zones marked by the coast and border areas with another ecosystem, or the fact that they are outside the study area, e.g., in another country (boxes in black in Figure 7A). The area of influence partly eliminates these drawbacks, because only the study area or areas that the patch can inhabit are used in its calculation. The problems and limitations shown in Table 4 are also present when tiling. These problems are solved using the area of influence, but there are differences among the dimensions and shapes of zones that should be considered in order to interpret results properly (Figure 7B). To solve this problem, a combination of tiles and PFI value might be more realistic (Figure 7C).

The area of influence is essential with regard to discovering the anthropic fragmentation of a patch, since some patches are small or distant from other patches, and may have a small patch fragmentation (Figure 3). This depends on the dynamics or the situation of the ecosystems. Although Voronoi triangles can be used to delimit the area of influence by means of the potential distribution of the patch, this can be even more precise if we introduce site variables such as very steep slopes, rivers, or roads [7]. The PFI groups the main fragmentation metrics [8,50,51] into one, thus improving patch fragmentation analysis and extrapolating at the landscape level for a more complete view of the fragmentation process [14]. The PFI has also been very efficient at identifying temporal dynamics of fragmentation through the analysis of hot spots. This makes it possible to take conservation or reforestation measures and attain a realistic view of the state and evolution of the patches and the landscape, in addition to allowing the study of landscape dynamics [35].
Table 4. Summary of the most common problems when measuring fragmentation with standard parameters.

| Metrics                     | Conclusions and Implications | Problem Description                                                                 | Graphical Representation |
|-----------------------------|------------------------------|-------------------------------------------------------------------------------------|--------------------------|
| Area                        | The larger the average area, the less fragmentation. | In figure A.1, there is a greater mean area; however, figure A.2 shows less fragmentation. | ![A1](image1) ![A2](image2) |
| Area/Perimeter              | The smaller the area/perimeter, the greater the fragmentation. | In figure B.1, there is higher area/perimeter; however, figure B.2 shows higher fragmentation. | ![B1](image3) ![B2](image4) |
| MPFD and other shape parameters. | In more complex forms, there is greater fragmentation. | In figure C.1, the patches have more complex shapes; however, figure C.2 shows greater fragmentation. | ![C1](image5) ![C2](image6) |
| Distance                    | The shorter the mean distance, the less fragmentation. | In figure D.1, the patches have a greater mean distance; however, figure D.2 shows greater fragmentation. | ![D1](image7) ![D2](image8) |
| Number of patches           | The lower the number of patches, the less fragmentation. | In figure A.1, there are fewer patches; however, figure A.2 shows less fragmentation. | ![A1](image1) ![A2](image2) |
| Core Area                   | Undisturbed areas within the patch—the greater the core area, the less fragmentation. | The core area is based on the species and on the area that the species needs eliminating the edge effect, but it starts from the premise that the edges are detrimental to the species, though this is not always the case. | ![A1](image1) ![A2](image2) |
The problems and limitations shown in Table 4 are also present when tiling. These problems and in blue areas of mountains. In the black boxes are mixing zones of ecosystems. (Figure 7).

The PFI calculation on the basis of tiles or hexagon tessellation allows for a better assessment of fragmentation at the landscape level, particularly where there are a high number of small patches. For example, in 1990, only 62 patches out of a total of 6908 were more than 10 km², but these patches occupied 85% of the forest area (and the historical trend was similar). This could lead to a distortion if the patch data are extrapolated at the landscape level [6]. Tessellation, therefore, helps to assess fragmentation at the landscape scale. Another advantage of tessellation is that, when using the area of influence in the PFI formula, it measures only the area in which the surface of ecosystems can increase, thus eliminating the problems of mixing with other ecosystems or other land uses (e.g., coastal zones or borders of countries).

4.3. Fragmentation Spatial Patterns

The analysis carried out by Getis-ord Gi * (hotspots) has been proven to be efficient at supporting decision-making [60,61], showing its importance with regard to helping to identify priority areas for policy. It allows policymakers to maximize the benefits of a preferred policy option, and facilitates decisions related to the optimized use of the land [62].

As our results show, the analysis of hot spots on the basis of areas of influence and not solely on a patch is also extremely efficient at identifying areas that are more prone to deforestation, which would indicate that those areas are the most threatened. The study of spatial patterns can help in decision-making by indicating those areas with concentrations of patches with a high or low risk of fragmentation (hot and cold spots, respectively). Moreover, the study of spatial patterns makes it possible to study the causes of the increase or decrease in fragmentation, such as the spatial coexistence of hotspots with human infrastructures and settlements [35].

5. Conclusions

Fragmentation is one of the main causes of the extinction of species, and it can be measured in several ways. The PFI is a new tool with which to describe and interpret habitat fragmentation. Most fragmentation metrics are designed for ecosystems whose fragmentation patterns are not very complex, such as the Amazon rainforest or the taiga, for example. The representation of the landscape is usually square or rectangular, but not all ecosystems have this structure, and the traditional metrics are not, therefore, very efficient, particularly when they are interpreted individually. In this respect, the fact that the PFI also includes the area of influence and shape complexity provides useful information about the patch fragmentation status. In summary, the PFI was able to improve the description of fragmentation status at the patch scale, indicating very large patches catalogued as highly fragmented or small patches classified as not very fragmented. The
PFI was effective at cataloguing the patch fragmentation, along with identifying patterns such as patch disappearance or conservation. Finally, the PFI has been applied in a highly fragmented forest with complex patterns of deforestation and fragmentation, and it would be interesting to apply it to other ecosystems with simpler patterns.

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**Appendix A**

$$PFI = \frac{4}{5} \left( 1 - \frac{Ap}{Ai} \right) + \frac{1}{5} x \left( \frac{MPFD}{2} \right)$$

Ap = 350000 m²  Ai = 3410000 m²  MPFD = 1.34645

$$PFI = \frac{4}{5} x \left( 1 - \frac{350000 m^2}{3410000 m^2} \right) + \frac{1}{5} \left( \frac{1.34645}{2} \right)$$

PFI = 0.852533

**Figure A1.** Demonstration of the calculation of the PFI of a patch, the Ap, Ai and MPFD are observed and how the mathematical formula is developed. MPFD according to McGarigal and Marks (1995).

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