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Article

Using Multitemporal Landsat ETM+ Imagery to Determine a Sustainable Exploitation Patterns of the Forest Resources in the Moldo-Transylvanian Carpathians - Romania

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Abstract: Monitoring the ratio of forested and deforested areas plays a key role in studying the dynamics of forest areas. Appropriate mapping of anthropogenic forest disturbances is particularly important in the context of sustainable forest management. It provides ecological, social and economic information which is crucial for forest policymakers. In the last two decades, the forest areas of the Moldo-Transylvanian Carpathians have been subject to a high rate of deforestation which at present state lacks proper quantification. We present a novel methodology for monitoring the forest disturbance dynamics in Moldo-Transylvanian Carpathians by use of fractal analysis including entropy, Fractal Fragmentation Index (*FFI*) and Tug-of-War lacunarity (Λ_{T-o-W}). This was necessary to quantify and identify the disorder (entropy), the fragmentation (*FFI*) and heterogeneity of the spatial distribution (Λ_{T-o-W}) patterns. Based on satellite images of the forest areas (annually 2000-2014), increased fragmentation was demonstrated by FFI increase, a measure of the degree of disorder (entropy) and heterogeneity (lacunarity). Our results revealed that textural and fractal analysis can be an effective tool for the extraction of quantitative information about the spatiotemporal dynamics of forest disturbance. The methods developed, and results obtained are a complementary approach to forest disturbance mapping (based on traditional image classification) for future development and adaptation of forestry management policies to ensure a sustainable management and exploitation of forest areas.

Keywords: forest disturbance; deforestation; sustainability; fractal analysis; entropy; forest management.

1. Introduction

Many studies have highlighted the dynamics of forests and the increasing importance of sustainable management policies [1,2,3,4]. Yet, in many parts of the word, deforestation occurs due to the increasing human population that requires even more arable land for agriculture [5,6]. Moreover, illegal logging and legal wood harvesting for industries also lead to deforestation [7,8]. Forest has several beneficial roles: reduction of water erosion, soil fertility enhancement, and air quality improvement. Forests also support and maintain high biodiversity, especially in areas with endemic species [9,10]. Forest areas also contribute to climate change mitigation through CO_2 storage, resulting in reduced atmospheric CO_2 [11-13]. Consequently, deforestation reduces the effectiveness of the CO_2 sequestration through forest growth [11].

Forest areas also provide a range of ecosystem services (natural capital) for local communities: forest products for subsidence needs, supplemental foods, and construction materials [14,15]. Thus, forest resources have a pivotal role as the foundation for economic development, especially in mountainous areas where this resource is abundant and is often the primary source of livelihood [2]. The benefit of forest areas is reflected in the ever-increasing industrial demand for wood [16,17]. Further, it should note that economic implications of deforestation could be both direct (wood harvest) and indirect (creation of markets for CO_2 sequestration or obtaining agricultural land due to deforestation). Many essential forest functions and resources have no immediate demands, and hence, no apparent economic value, thereby justifying the conversion of forest land for other purposes. About 41% of European mountains are covered by forests [18]. The Carpathian Mountains represent the most massive mountain range in Central Europe and the second largest in Europe with a length of about 910 km within Romanian borders [18,19]. The most substantial forested area in Romania is in the Carpathian Mountains (covering 51.9% of total national forested areas) [20] with almost 60 000 jobs directly related to wood harvesting that require extensive management of this resource [21, 22].

The changes of the policy of land use after the communist period created a tremendous amount of ownership changes from state to private-owned forests as in case of Poland [23], Slovakia [24,25] and Romania [7,26]. So, the permissiveness of land use laws determined the decrease of forest areas. In this respect, practical solutions to protect forest resources have become an essential agenda for policymakers [27,28]. The monitoring of forest areas changes become a priority for authorities [29]. A lot of modern technologies were used in investigations to quantify the land cover and land use change over time. Specifically, recent studies based on fractal analysis of remotely sensed imagery have proven successful in quantifying the spatial pattern of the forests, deforestation or reforestation (e.g., quantifying spatial metrics such as lacunarity, fractal fragmentation). [30,31].

Because the shapes of forest areas are morphologically complex, fragmented, uneven and because standard descriptors depend on the scale of observation [32], we propose an invariant scale analysis as fractal analysis. The utility of fractal analysis in forest research was demonstrated previously by our research team [31,33,34]. Fractal analysis is a powerful tool both for describing irregular objects in nature because they cannot be defined by classical Euclidean geometry [35] and for measuring seemingly random or too complex patterns. Previously studies by our research team [31,33,34] focused on the spatiotemporal dynamics of fragmentation and heterogeneity forests, by fractal analysis.

In this study, made a step forward and we used textural and fractal analysis to quantify the patterns of the dynamics of forest areas in Moldo-Transylvanian Carpathians, Romania between

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2000 to 2014 to obtain spatiotemporal information about deforestation and reforestation. Our paper is a novelty in the field, as it explores the spatial patterns of deforestation. The metrics provided by the fractal analysis goes beyond traditional per-pixel forest change detection mapping and allows for quantification of the complexity of the spatial structures such as textural uniformity of the forest coverage per image pixel, and the spatial effects of the deforestation quantified through the fragmentation/compactness and lacunarity. Thus, the metrics produced from the fractal analysis offers some information about shape descriptors for decision makers within forest use analysis and forest resource adaptation to changing economic demands. Changes in forest policy and management have caused essential changes in forest pattern, and these are associated with necessary changes in forest ecosystem processes.

2. Materials and Methods

2.1. Study area

Moldo-Transylvanian Carpathians are a subunit of the Eastern Carpathians and are bounded by the North Carpathian Mountains in the north and by the Curvature Carpathian Mountains in the south (Figure 1). With a diversity of landscapes imposed by the geologic mosaic this mountainous area is divided into three sub-regions: the volcanic rocks in the western part (Călimani, Gurghiu and Harghita Mountains), the crystalline schist rocks (Bistriței, Ceahlău and Tarcău Mountains), (Giurgeu, Ciuc and Nemira Mountains) and the flysch rocks (Stânișoarei, Goșmanu and Berzunți Mountains). These sub-regions are separated mainly by three depression areas: Giurgeu, Ciuc, and Comănești. These mountains are covered by tree species as Mountain Pine (*Pinus mugo*), spruce (*Picea abies*), fir (*Abies alba*), oak (*Quercus robur*) and ash (*Fraxinus excelsior*) [36] and overlap with the four most deforested counties of Romania (Suceava, Neamț, Bacău and Harghita).

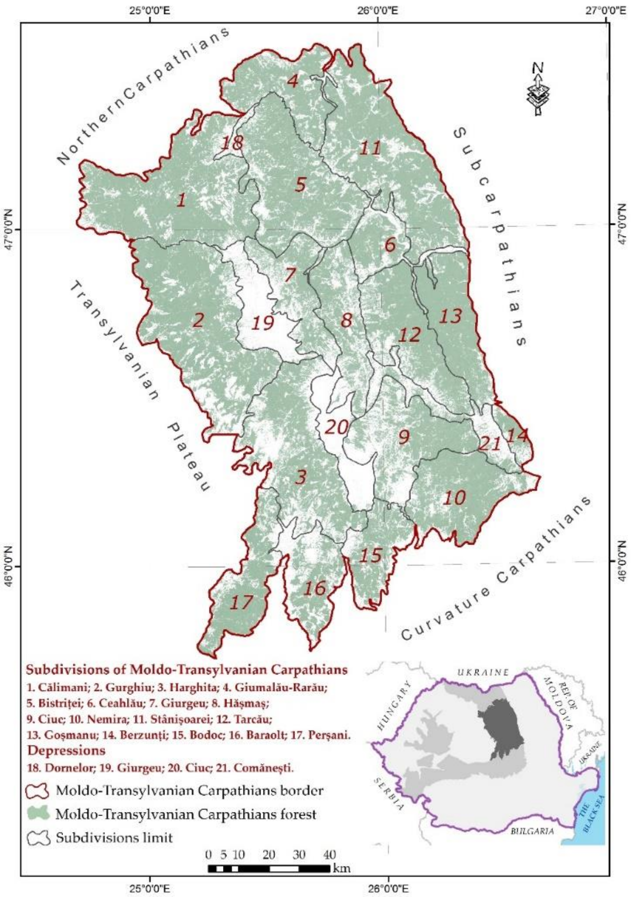

Figure 1. The geographical study area of the Moldo-Transylvanian Carpathians.

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2.2. Preprocessing algorythm of the Satelite images for analysing the deforestation

The source of the remote sensing imagery for the current study is the Global Database from the Department of Geographical Sciences, Maryland University [37]. Images are from the Landsat 7 ETM+ satellite images with a spatial resolution of 30 meters from the year 2000 to 2014 [37]. In the analyses, we used images classified into forested areas (annually 2000-2014), for deforested areas (annually 2001-2014) and the reforested areas only a single synthetic image from 2001 to 2014 (a single image containing all the regeneration from 2001-2014) [37]. We have processed these TIFF encoded time series of Landsat images (Table 1) to extract deforested and reforested areas as described in more details in [34]. Subsequently, images were transformed into binary images using default binary function from ImageJ 1.51 software [38] and analyzed using a macro for calculating the area and the percentage of forest pixels (Figure S1 in Supplementary Materials). For the grey-scale analysis, we used 8-bit images of annual canopy forest cover maps or annual disturbance maps. For the analysis of fractal indexes (*FFI* and Λ_{T-o-W}) were used binary images and for Gray-Level Co-Occurrence Matrix (GLCM), were used 8-bits images. The results of GLCM and fractal analysis, obtained in ImageJ and IQM softwares, that describes the spatial effects of deforestation on the integrity of forests were analysed comparatively with the values obtained in ArcGIS software (ArcGIS 9.3.1.

Table 1. Landsat 7 ETM+ image paths and rows covering the study area [34]

Satellite images	Resolution	Longitude	Latitude	Paths	Rows
LANDSAT 7 ETM+	30 m	50°0′ N	20°18′ E	188	25
LANDSAT 7 ETM+	30 m	50°0′ N	30°18′ E	181	25
LANDSAT 7 ETM+	30 m	39°60′ N	20°18′ E	185	32
LANDSAT 7 ETM+	30 m	39°60′ N	30°18′ E	179	32

We analyze the coverage of forest on a per-pixel basis, at a pixel resolution of 30 m, as a function of the degree of forest coverage from 0% to 100%. We defined five classes (0-20%; >20-40%; >40-60%; >60-80%; >80-100%) in the software ArcGIS and produced a series of images in 8-bit grey-scale format covering forested, deforested and regenerated areas using ArcGIS software). We have divided into five classes to see what the major forest cover of the pixel is dominant for both forests, deforestation, and regeneration.

2.3. Entropy and Fractal Analysis

There is one major problem with the methods in that there are detailed descriptions of calculations of entropy, FFI, and lacunarity. However, there is no context as to what these metrics tell us, why they are important, or how we'd expect them to change over time and space. Please expand the context of these measurements. Lastly, there are some organizational problems that make this section difficult to follow.

The degree of disorder of forested areas (imposed by forest disturbance) is important, as it provides additional information about the differences of the spatial pattern of deforestation and regeneration and their impact on the forest, including the degree of forest cover of pixels. The degree of disorder was determined by computing the entropy using the GLCM plugin [39] in ImageJ [38]. GLCM, also known as the grey-level spatial dependence matrix, is a statistical method of examining texture that considers the spatial relationship of pixels. The GLCM functions characterise the texture of an image by calculating how often pairs of the pixel with specific values and in a specified spatial relationship occur in an image, creating a GLCM, and then extracting statistical measures from this matrix (provide information about shape, i.e., the spatial relationships of pixels in an image.) The GLCM is calculated how often a pixel with grey-level (grayscale intensity or tone) value i occurs either horizontally, vertically, or diagonally to adjacent pixels with the value j.

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The entropy is significant when the image is not texturally uniform and when many GLCM elements have small values. Complex textures tend to have high entropy. The entropy is measured according to Equation (1) [39].

$$Entropy = \sum_i \sum_j p(i,j) \log p(i,j) \quad (1)$$

where $p(i,j)$ are spatial co-occurrence probabilities and i and j are coordinates of the co-occurrence matrix.

Fractal analysis is applied by using the Fractal Fragmentation Index *(FFI)* plugin [40], and the Tug-of-War Lacunarity analysis was conducted using the Frac2D plugin [41] in the IQM 3.2 software [42].

The Fractal Fragmentation Index (*FFI*) is a fractal index that quantifies the degree of fragmentation for the fractal objects and can be interpreted as a compaction index [31]:

$$FFI = D_{B-C}A - D_{B-C}P = \lim_{\varepsilon \to 0}\left(\frac{\log N(\varepsilon)}{\log\frac{1}{\varepsilon}}\right) - \lim_{\varepsilon \to 0}\left(\frac{\log N'(\varepsilon)}{\log\frac{1}{\varepsilon}}\right) (2)$$

where $D_{B-C}A$ is the box-counting fractal dimension of the summed-up areas and $D_{B-C}P$ is the box-counting fractal dimension of the summed-up perimeters, ε is the side length of the box, $N(\varepsilon)$is the number of contiguous and non-overlapping boxes required to cover the area of the object and $N'(\varepsilon)$ is the number of contiguous and non-overlapping boxes required to cover just the perimeter of the object [43,44].

In our case, y [31], *FFI* = 0, when $D_{B-C}A = D_{B-C}P$. This is the case when the forested areas are very small appearing as point-like objects in the image. *FFI* values close to zero are obtained for small and highly fragmented forest areas, while values close to one represent more compact forest areas, which are arranged in clusters.

Fractal fragmentation is very useful in estimating compactness/fragmentation of fractal and natural objects that do not follow the classical geometry. However, self-similar objects, such as forests, with an identical fractal dimension may differ significantly in their textural appearance [45]. So, the use of only fractal fragmentation is therefore not useful to discriminate against objects, while the fractal dimension quantifies the way of occupying space and the lacunarity completes the fractal dimension with its ability to quantify how space is occupied. Moreover, lacunarity discriminates the spatial distribution of gaps in texture, at multiple scales, and is not sensitive to the edges of the images. In our research, we used the Tug-of-War algorithm lacunarity.

Tug-of-War lacunarity is useful in determining the way the deforestation and reforestation are done: homogenous – organized or heterogonous– disorganized, and their effect on forest areas. Tug-of-War lacunarity [41] was calculated based on the equation:

$$\Lambda_{T-o-W} = \frac{N(r)Z^2}{L^2} \quad (3)$$

with $N(r)$ is the number of boxes,

Z^2 is the second moment for each width as the median of s_2 values, each is the mean ofs_1 squares of the counter values.

$s_1$and $s_2$are two predefined parameters that indicate the accuracy and the confidence.

Finally, $L^2 \approx \left(\sum_{i=1}^{N(r)} p(r,i)\right)^2$, where $p(r,i)$ is the number of occupied sites in the i-th box. The Tug-of-War lacunarity parameter indicates mainly the manner of deforestation where increasing values indicate the chaotic distribution of the deforestation and vice versa.

The steps followed in the analysis are presented in the flowchart of image pre-processing, GIS and fractal analysis (Figure 2).

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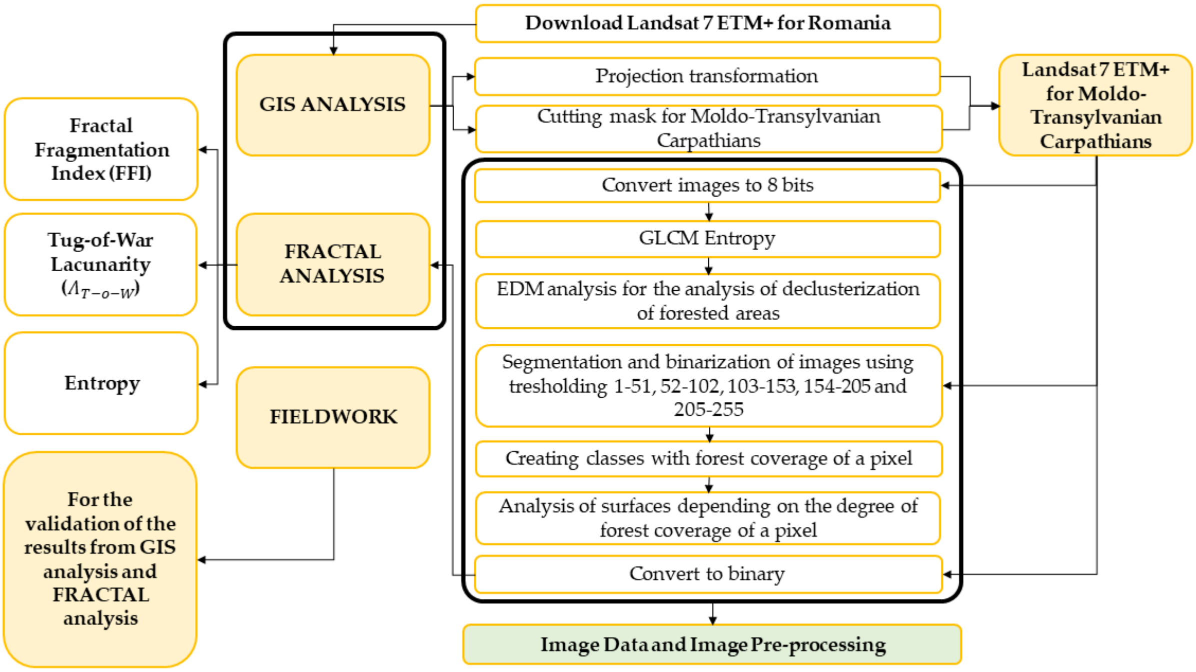


Figure 2. Workflow of data pre-processing, GIS analysis and fractal analysis of deforestation processes for Moldo-Transylvanian Carpathians

2.4. Fieldwork

We identified for the fieldwork four case studies from Moldo-Transylvanian Carpathians (Călimani, Giurgeu, Hășmaș and Tarcău Mountains) (Figure 1) to perform the field data collection activities described below. The fieldwork was performed in the summer season, over a period of two weeks during the late summer of 2017, to have the conditions to make differences among deforested and forested areas.

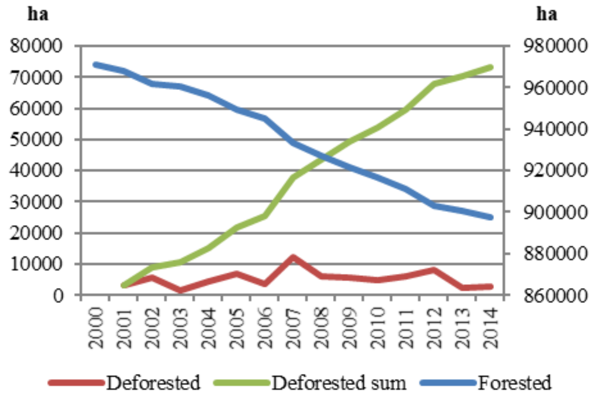
The field work focused on the gathering of valuable visual inspection of structural information on forest distribution to validate the general focus of the paper. The analysis of satellite images conducted to the field validation for the assesses the fragmentation of forests. So, where established from the analysis of satellite images the relevant case studies for the field work. The fieldwork has materialized the hypothesis regarding the areas where the forests have been deforested but also the intensity of the deforestation,

Within each of the four case studies, detailed and spatially representative GPS recorded photographs were conducted. Kodak Easyshare C613 Zoom Digital Camera was used to take photographic documentation for all observations.

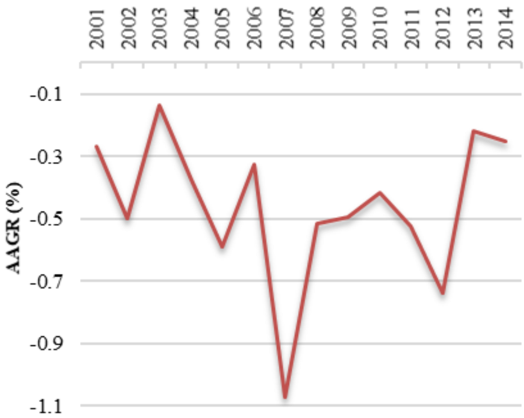
3. Results

3.1. Deforested and forested areas from Moldo-Transylvanian Carpathians

In the Moldo-Transylvanian Carpathians, the general decrease of the forested areas during 2000-2014 was observed, however with considerable inter-annual variability (Figure 3a).



(a)



(b)

Figure 3. (a) Dynamics of forested, deforested and deforested sum areas in the Moldo-Transylvanian Carpathians between 2000 and 2014. The primary y-axis corresponds to the forested and deforested areas and secondary y-axis to the deforested sum;**(b)** Average Annual Growth Rate (AAGR) of forested areas in the Moldo-Transylvanian Carpathians in 2000-2014.

Forested areas have continuously decreased during the period of analysis covering 970,858 ha in 2000 and 897,571 ha in 2014, indicating a decrease of 7.5%, but with some inter-annual variability. 2007 and 2012 were characterized by the highest average annual decreases, and the lowest values were observed in 2003 and 2013-2014 (Video S2 in Supplementary Materials). In total 73,286 ha were deforested during the entire period of analysis (2000 to 2014) corresponding to a reduction in forested area by 6.43 %. Only 54,222 ha were reforested in the corresponding period yielding a deficit of 26 %. This is highlighted by the Average Annual Growth Rate (the average increase/decrease in forested areas as a function of time) (Figure 3b). The Annual Average Growth Rate (AAGR) was obtained according to the formula:

$$\text{AAGR for 2001} = \frac{\text{forests areas for 2000} - \text{forests areas 2001}}{\text{forests areas for 2000}} * 100$$

It is a negative or decreasing rate of growth because the net forested areas are reduced from year to year. Until 2004, the deforestation is shown to be dispersed in small patches, but from 2005 and onwards clustering of deforestations can be observed. Such clusters appeared primarily in the Călimani, Gurghiu, Giurgeu and Ciuc Mountains. This coincides with an overall diminishing of clusters for the forested areas (Video S2 in Supplementary Materials).

Analysis of five classes of canopy cover metric that was summarized at a larger scale (30x30 pixel resolution on Landsat 7 ETM+, in gray-scale) in the 2000-2014 period showed that 78% of the pixels of forested areas had a forest coverage of over 80%, followed by 11% of the pixels with a coverage of >60-80%, 6% of the pixels with a coverage of >40-60%, 3% with>20-40% and finally 2% with 0-20% coverage.The analysis of deforested areas showed that the deforestations occurred mainly in areas of dense forests where forest coverage was >80%, followed by >40%-60% and >0%-20% (Figure 4). In areas where the forest coverage of pixel was between 20% and 40% or between 60% and 80%, no deforestation was recorded. As for Figure 3a, 2007 and 2012 were characterized by the highest average number of annual deforested areas for all forest cover classes. The lowest values for all forest cover classes were observed in 2003 and 2013-2014.

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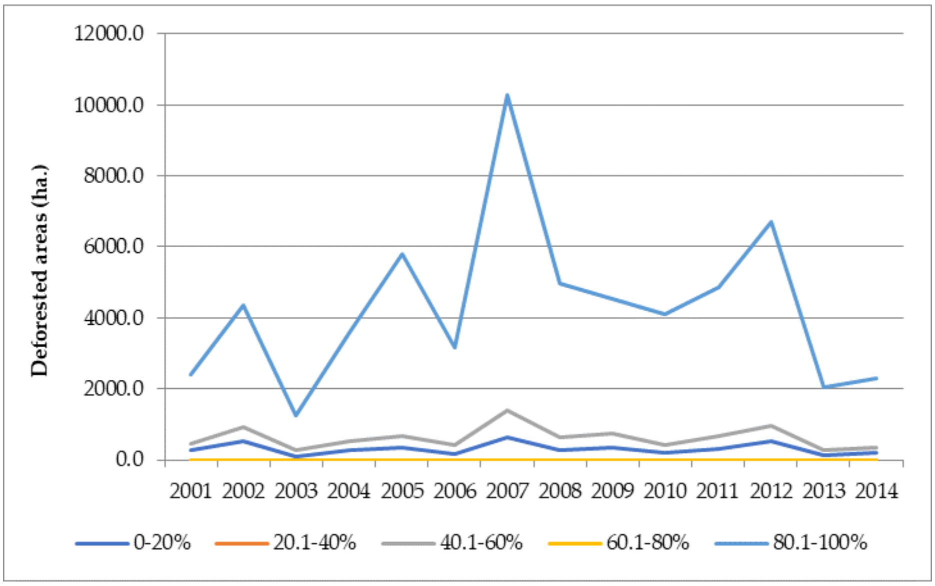

Figure 4. Deforested areas (2001-2014) based on pixels divided into different intervals of forest cover (0-20% with blue; 20,1-40% with dark red; 40,1-60% with green; 60,1-80% with purple; 80,1-100% with light blue.

3.2. Entropy

The entropy of forest areas was relatively high and steadily increasing from 1.37 in 2000 to 1.415 in 2014 (indicating an increase of 3.2% of the degree of disorder of deforested areas, after deforestation) (Table 2). The main reason is a very different pattern of deforestation. However, the entropy values of the deforested areas were relatively small and constant over the period 2000-2014. Only two slight peaks (>0.03) occurred in 2007 and 2012 coinciding with the greatest deforestation rates. The lowest values of entropy (<0.015) coincide with the lowest deforestation rates, which occurred in 2003 and 2013-2014.

The entropy of reforested areas for 2001-2014 was less than the entropy of the deforested areas (0.144 versus 0.213) indicating that the deforestation produced more disorder in forested areas than is the case for reforestation processes (Figure 5a).

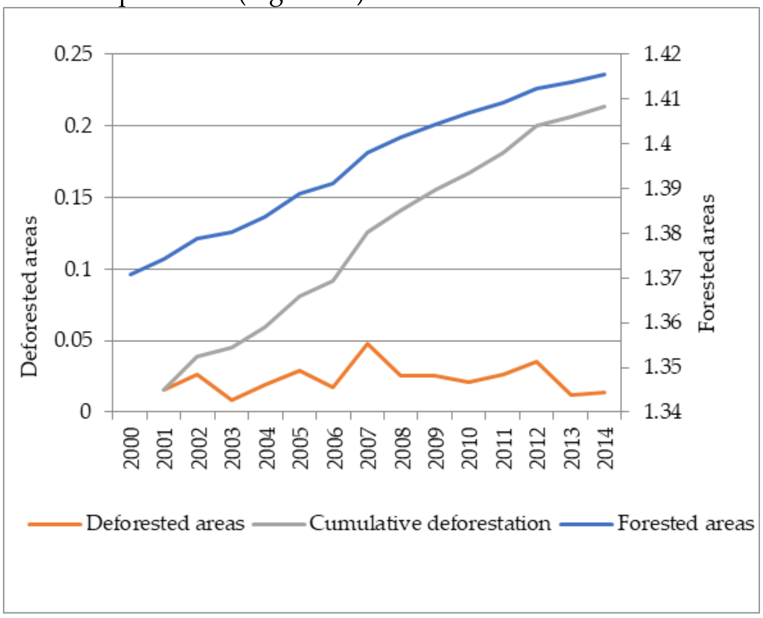

Figure 5 (a) Dynamics of GLCM Entropy

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3.3. Fractal Fragmentation Index (FFI)

For the analyzed period, *FFI* was reduced from 0.15 (2000) to 0.12 (2014) indicating a continuous growth of fragmentation of forested areas, especially in Călimani, Gurghiu, Goșmanului Mountains, with a diminution or even destruction of clusters of forested areas. The decrease of *FFI*, which indicates the increase in fractal fragmentation, is generated by the fragmentation of the patches, but also to the increase in their number by the detachment of the compact surfaces following the deforestation (Figure 5a).

The fragmentation of the deforestation during 2001-2007 was very low, the *FFI* values been between 0.001 (2001) and 0.006 (2007). Slightly more compacted deforestation with values >0.003 occurred in 2004 and 2007, while fragmented deforestations with values <0.001 were recorded in 2001, 2003 and 2013-2014 (Figure 5b). The average *FFI* value for reforested areas was 0.0015 between 2001-2014, which is lower than for deforested areas due to the fragmented appearance of reforestation.

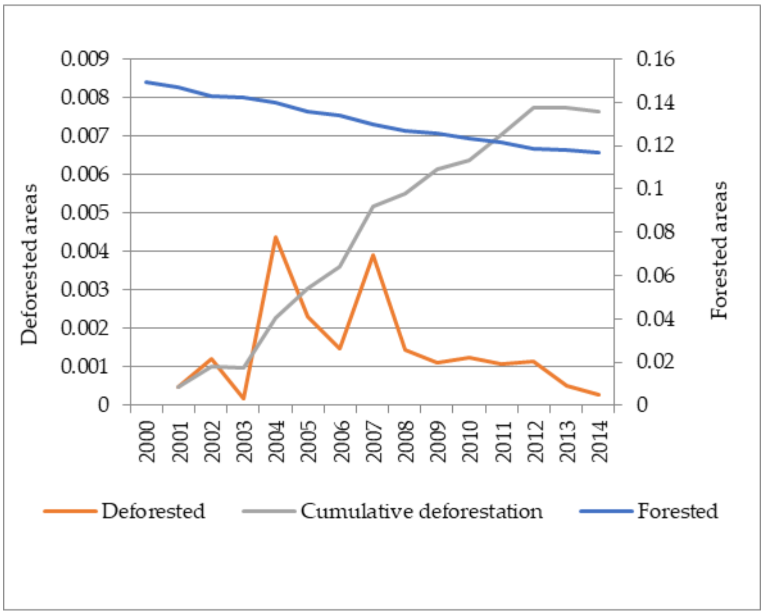

Figure 5 (b) *Dynamics of Fractal Fragmentation Index* (***FFI***)

3.5. Tug of War Lacunarity (Λ_{T-o-W})

The degree of heterogeneity of forest areas was calculated using Λ_{T-o-W} that highlighted the effects of deforestation on the compactness of forested areas. The lacunarity of forest areas decreased from 0.15 in 2000 to 0.14 in 2014 due to the deforestation, with small variations. An accentuated clustering of the deforestation (low values of Λ_{T-o-W}) corresponded with homogenous and compacted deforestations (lowest in 2004 and 2011) in comparison to years with more heterogeneous and fragmented deforestations in 2003 and 2013 (Figure 5c).

The most heterogeneous manifestation of deforestation ($\Lambda_{T-o-W} > 1$) occurred in 2003 and 2013-2014, during the most homogenous deforestations in a more compact manner with $\Lambda_{T-o-W} <$ 0.8 were in 2007 and 2012.

For the period between 2001 and 2014, the Λ_{T-o-W} values of reforested areas exceeded the values of deforested areas (0.526 compared to 0.522) confirming that the reforestation was more heterogenic than the deforestation because the regeneration is more chaotic.

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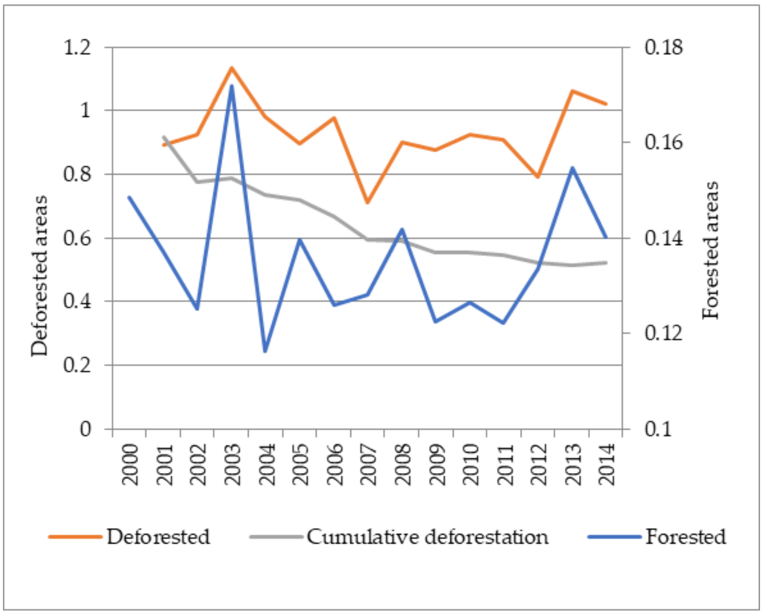

Figure 5 (c) Dynamics of Tug-of-War Lacunarity ($\Lambda_{T\text{-}o\text{-}W}$).

3.6. Case studies for Călimani, Giurgeu, Hășmaș and Tarcău Mountains

3.6.1. **Călimani Mountains** are located in the NW part of the Moldo-Transylvanian Carpathians and are neighboring the Northern Carpathians in the northern part, Transylvanian Plateau in the West, Bistriței Mountains in the East and Gurghiu Mountains to the South. The Călimani Mountains was declared a National Park in 2000, to sustain the biodiversity of flora, fauna and natural habitats on an area corresponding to 24,041 ha. The fractal indicator, *FFI* of the forested areas, reduced from 0.313 (2000) to 0.225 (2014) revealing a growth of the fragmentation of the forested areas and a diminishing of the forest's clusters (Figure 7c). The $\Lambda_{T\text{-}o\text{-}W}$ of the forested areas showed variations of the lacunarity of the forests in function of the deforestation pattern from 2000 to 2014 (Figure 8d). Cumulative deforestation was recorded in the northern part of the mountains since 2001 and have been increasing gradually until 2014 for large parts of the region (Figure 8a); a development which is supported also by the creation of forest roads, that facilitates the accessibility and thereby the exploitation of forest resources (Figure 6 a, b).

(a)

(b)

Figure 6. Photos from **(a)** Rarău Mountains and **(b)** Călimani Mountains showing areas of both deforestation and regeneration. In figure **(b)** foreground - deforestation in Călimani Mountains and natural reforested areas and old forests in the background. Photos: field work summer 2017 (Ciobotaru, A-M.).

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3.6.2. **Giurgeu and Hăşmaş Mountains** are located in the central part of Moldo-Transylvanian Carpathians in the south-eastern part of the Călimani Mountains. In the northern part of the study area, they are neighbored by Giurgeu Depression, in the north by Călimani and Bistriței Mountains and in the south by the Ciuc Depression. Substantial deforestation also characterizes these mountains since 2001 (Figure 7b, 7c) explaining, in part, the accessibility in this mountain area, due to the presence of depression areas that surround the mountains. A boom of deforestation was recorded in 2007, with the rapid growth of deforested areas and these mountains are at present amongst the most deforested in the entire Moldo-Transylvanian Carpathians. *FFI* have small values in Giurgeu Mountains and also in Hăşmaş Mountains because of a small degree of fragmentation caused by the geomorphology of the river valley and deforestation (Figure 8a).

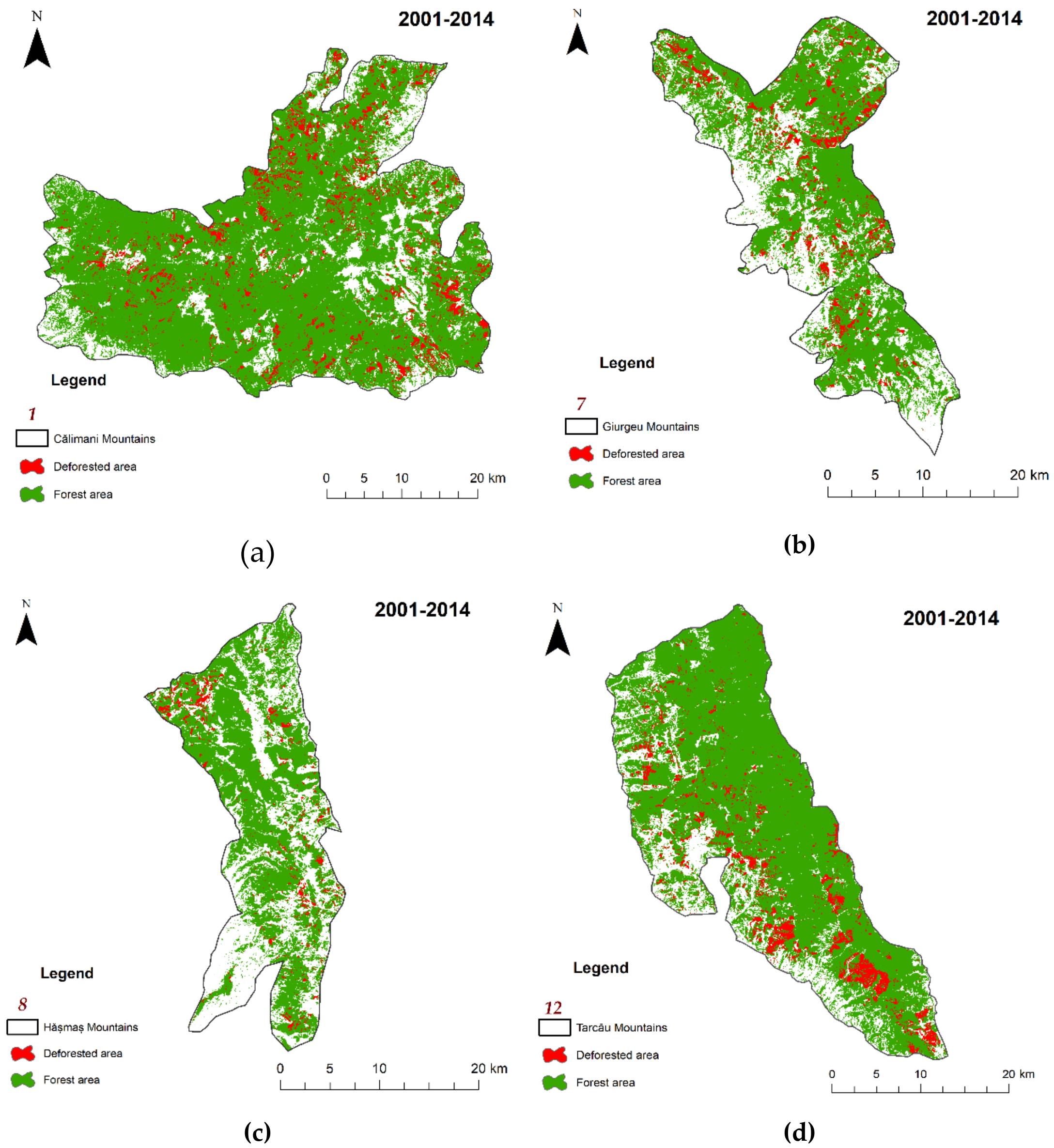

Figure 7. The extent of the deforestation process. **(a)** Călimani Mountains; **(b)** Giurgeu Mountains; **(c)** Hăşmaş Mountains; **(d)** Tarcău Mountains (numbers from each map represent the corresponding number from Figure 1). Detailed maps for each year of the period analyzed are available at Figure S3 a, b, c, d in Supplementary Materials).

Hăşmaş Mountains has been a protected area since 1990, belonging to the Bicazului Gorges-Hăşmaş Mountains, and included in the 4th IUCN (International Union for Conservation of

Nature) category. Totalizing 6793.64 ha, the primary purpose of establishing this protected area is to preserve the biodiversity and landscape.

3.6.3. **Tarcău Mountains** are located in the eastern part of the Moldo-Transylvanian Carpathians, in the northern part of the Comănești Depression. The analysis of the Landsat 7 ETM+ revealed that the deforestation process began in 2004 in small patches in the areas close to the Trotuș River. As a characteristic of all case studies analyzed, Tarcău Mountains show more deforested areas from the beginning of 2007, the year when Romania became a member of the E.U. The areas were gradually influenced by improved access to the forest resources which is reflected by an increase in $\Lambda_{T\text{-}o\text{-}W}$ compact deforestations and an increase of fragmentation of forested areas. As in the Călimani Mountains, the cumulative deforestation in Tarcău Mountains $\Lambda_{T\text{-}o\text{-}W}$ was reduced considerably indicating that the deforestations were made primarily through agglutination (in addition of the deforested areas) (Figure 8b). The deforestation process continued in the same areas throughout analysis by gradually continuing deforestation in adjacency to already deforested areas causing the areas of deforestation to appear in large clusters (Figure 7d).

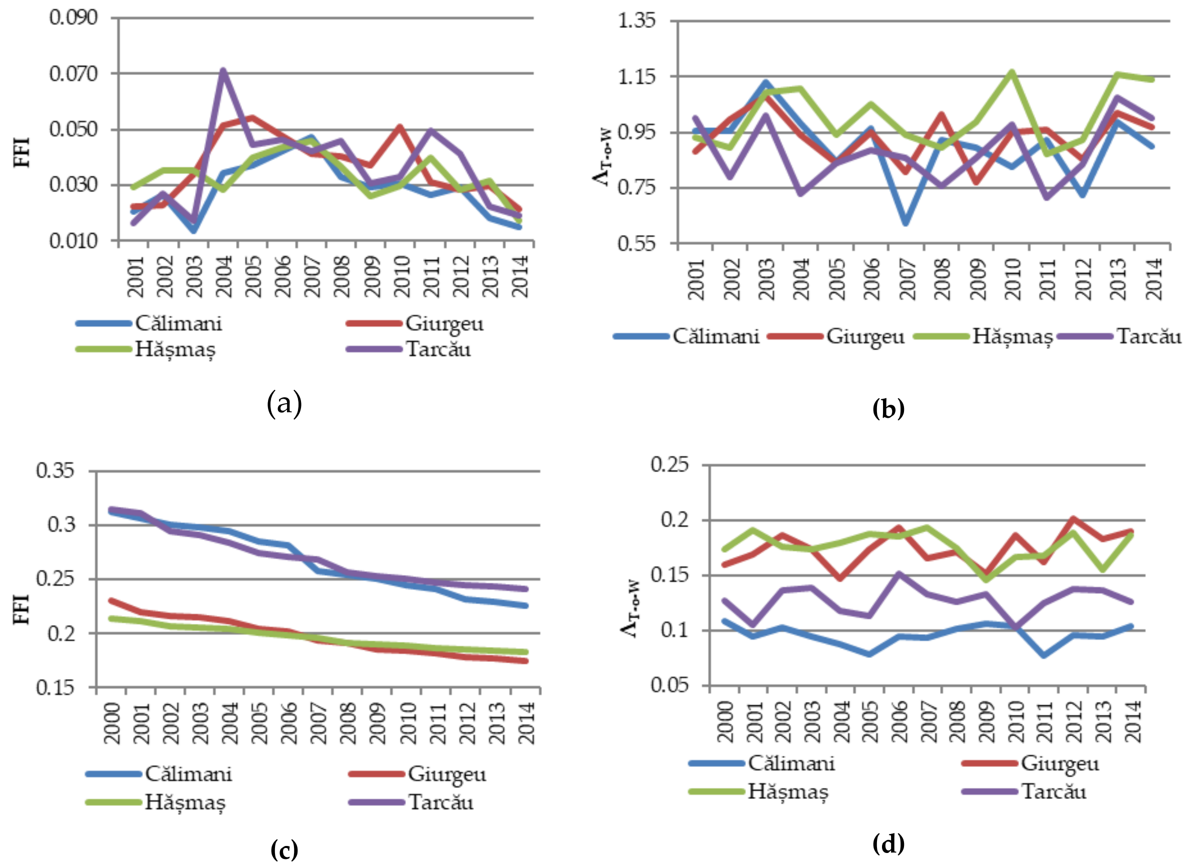

Figure 8. Dynamics of the fractal analysis indicators for the four case study regions**(a)** *FFI* of deforested areas; **(b)**$\Lambda_{T\text{-}o\text{-}W}$ of deforested areas; **(c)** *FFI* of forested areas; **(d)** $\Lambda_{T\text{-}o\text{-}W}$ of forested areas.

As the results of Figure 8 (a) and (b) show similar relative values, this suggests that deforestation processes overall similarly affect the whole Moldo-Transylvanian Carpathians. Analysis of *FFI* indicated more compact deforestation in Tarcău and Giurgeu Mountains and more homogeneous ones in Călimani and Tarcău Mountains. Figure 8(c) and (d) show a significant difference between the impact of deforestation on the forest areas of the Călimani and Tarcău Mountains towards Giurgeu and Hășmaș. In Hășmaș and Giurgeu Mountains more forest fragmentation is recorded (*FFI* = 0.21 - 0.23 in 2000 and 0.17 - 0.17 in 2014). The Călimani and Tarcău Mountains have more *FFI* forest compaction with higher values in 2000 (*FFI* =0.31 - 0.32) and 2014 (*FFI* =0.23-0.24). Our results show that, after 15 years of deforestation, the forest fragmentation of

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Călimani and Harghita Mountains has developed in a way that it resembles the forest fragmentation of Giurgeu and Hășmaș Mountains. The degree of heterogeneity of deforestation and the impact on forest homogeneity related to $\Lambda_{T\text{-}o\text{-}W}$ offers the same net differentiation between Călimani-Tarcău and Giurgeu- Hășmaș Mountains. Smaller values of the $\Lambda_{T\text{-}o\text{-}W}$ lacunarity are found in Călimani and Tarcău indicating a higher homogeneity of the forests of Giurgeu and Hășmaș Mountains and a lower effect in the break-down of the clusters due to deforestation.

4. Discussion

Analysis of the deforestation patterns from satellite images through fractal analysis is expected to facilitate the development of a method, together with other well-known fractal methods and may provide valuable complementary information to currently available methodologies in the field of forestry research. The results of deforestation patterns in Moldo-Transylvanian Carpathians, based on Landsat ETM+ analysis [31,46], was performed for the period 2000-2014 using fractal indexes: *FFI*, $\Lambda_{T\text{-}o\text{-}W}$ and different fractal dimensions. Computation with the ImageJ program allowed for the determination of fractal dimensions for deforested areas and the maps generated from four case studies showed different spatiotemporal deforestation patterns of forests from the mountain area of Moldo-Transylvanian Carpathians.

The main results of our paper confirm the results of previous research on deforestation analysis in Romania, but we bring a scientifically value, by identifying some patterns of deforestation. According to [7,47,48], high levels of logging have recorded due to legislative changes in conjunction with the EU integration of Romania, since the 1st January 2007. The forest areas have decreased during the last decade, as a response to the needs for timber and financial benefits of forest exploitation and wood exports. Differences that exist between historical forest management and contemporary forest patterns, with an increase of coniferous species were confirmed by [48]. Research in the Italian Alps also shown that mountain landscapes are vulnerable to environmental changes caused by extensive logging activities and poor management practices [4,49].

In the Romanian Carpathians, several studies [33,47,50] have presented an analysis of deforestation using satellite images. Similar to what was reported from the Alps, by [4,49] a study by [46] investigated spatial changes of forest resources in Northern Carpathians and their economic impact. These results were followed up by a study of [34] that confirmed high rates of deforested areas in mountainous areas based on the use of different fractal dimensions. Field validation in summer 2017 conducted by the authors of this study confirmed that the high areas of deforested areas and illegal logging are located mostly in Călimani, Rarău, Giurgeu and Hășmaș Mountains. The decreased forest areas during the last decades as a response to needs for timber and financial benefits were also mentioned by [17,28,48]. The restoration of forest landscape (FLR) and the increasing necessity of wood and ecosystem services for communities were also described by [17].

A multi-objective model for the planning of timber production forest and contribution for an efficient management plan and analysis of the trade-offs between economic and ecological objectives is presented by [28]. We provide, in conjunction, an analysis of textural and fractal algorithms for useful analysis of deforestation patterns in Moldo-Transylvanian Carpathians based on high-resolution images (Λ_{T-o-W}). The role of Landsat ETM+ in the analysis of the deforestation patterns is well known. Landsat imagery offers the advantage of having repetitive data coverage of relatively high spatial resolution. From the fractal analysis, conducted on forest areas from Moldo-Transylvanian Carpathians, we concluded that a continuous decrease of forest areas has occurred during the period of analysis, however with a considerable inter-annual variability. The reforestation was more heterogeneous and fragmented compared to the deforestation for the entire study area; the Λ_{T-o-W} of reforested areas were higher than the Λ_{T-o-W} of the deforested areas because the regeneration was made in a chaotic manner. In the Călimani and Tarcău Mountains, the value of Λ_{T-o-W} for reforestation was higher than the value of Λ_{T-o-W} for deforestation suggesting that the deforestation was more compact and homogeneous than the reforestation. The situation was found to be opposite for the Giurgeu and Hășmaș Mountains where the deforestations was observed to be more scattered and heterogeneous.

As can be observed from figure 6, there is a general trend that the deforestation is occurring about accessibility to roads especially, causing the coniferous forests to be cut due to their economic value. To this end, [51] highlighted the recreational value of the forests, in mountain forests in Europe, beneficial for incomes of local livelihoods. The Moldo-Transylvanian Carpathians constitute a high recreational value in Călimani and Tarcău Mountains, but, unfortunately, this economic value of the mountains is not harnessed correctly. Fieldwork in these case study areas confirmed the loss of old forests, especially in Călimani Mountains, likely because of inadequate planning management.

Our results showed that the most deforested areas occurred in regions with high accessibility, in the depression areas of Moldo-Transylvanian Carpathians. Assessing the deforestation patterns and the resulting environmental impacts are important, and our maps of deforested areas can aid to this end. The use of the Landsat ETM+ satellite images can provide the necessary baseline for the economic and social information, to be a real guide for forest and land use policy makers of the territorial administrative units involved.

Understanding the deforestation patterns in the Moldo-Transylvanian Carpathians, Romania using Landsat ETM+ is important for assessing the dynamics of forest areas to provide socio-economic information for forest policymakers from territorial-administrative units. Here, we show a methodology to monitor the forest dynamics based on fractal analysis.

5. Conclusions

Here we provided an analysis of Landsat ETM+ satellite images at 30 m resolution in Moldo-Transylvanian Carpathians providing quantitative information describing the spatial and temporal dynamics of deforestation and reforestation during the period of analysis (2000-2014). Based on the fractal analyses for quantification of irregular spatial structures, we obtained new information about deforestation as described by textural uniformity, compactness and chaotic distribution of the forest disturbance processes. The analysis of fractal indicators ($entropy$, Λ_{T-o-W} and FFI) describes and quantify the textural uniformity, compactness and chaotic distribution of the disturbance processes of deforestation. Overall, the Moldo-Transylvanian Carpathians is a region with high deforested areas and specifically it has been demonstrated that in the case studies analysed (Călimani, Giurgeu, Hășmaș and Tarcău Mountains) a high rate of deforestation exists. It is concluded that fractal analysis of deforested areas is a new tool for quantifying heterogeneity in quantifying the degree of homogeneity or spatial heterogeneity of deforested areas. Analysis of the degree of textural disorder of deforestation in forested areas provides essential information to identify efficient methods for managing legal as well as illegal logging. Such quantitative metrics can also assist in identifying the anthropogenic forest disturbance impact on territorial systems including biodiversity, local economies and guidance for police makers from deforested territorial administrative units, from Moldo-Transylvanian Carpathians.

Supplementary Materials: The following are available online at www.mdpi.com/link, Figure S1: Macro used in ImageJ 1.51 program; Video S2: Video material presents the extension of the deforested areas in Moldo-Transylvanian Carpathians (2000-2014). In red pixels, the deforested areas are illustrated. The green pixels represent forests from the study area; Figure S3a: The extent of deforestation process in Călimani Mountains for period 2001-2014; Figure S3b: The extent of deforestation process in Giurgeu Mountains for period 2001-2014; Figure S3c: The extent of deforestation process in Hășmaș Mountains for period 2001-2014; Figure S3d: The extent of deforestation process in Tarcău Mountains for period 2001-2014.

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