Spatial evolution of forest areas in the northern Carpathian Mountains of Romania

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In this study, we used fractal analysis to monitor the space-time evolution of forest areas. By this method, we observed the degree of fragmentation/compaction and heterogeneity/homogeneity of forested, deforested and reforested areas. Changes undergone by the forest areas were analysed for the Northern Carpathian Mountains of Romania, the mountainous area that suffered the most extensive transformations in this respect, in Romania. The database used satellite images 654178 Landsat 7 ETM + for the period 2000-2014. For the assessment of forest areas, the database provided by the Department of Geographical Sciences, Maryland University for the 2000-2014 period, was used. The Fractal Fragmentation Index (FFI), Fixed Grid 2D Lacunarity (Λ_{FG2DL}) and Tug-of-War lacunarity ($\Lambda_{T\text{-}o\text{-}W}$) were used to monitor the degree of fragmentation of forested areas, respectively, the degree of heterogeneity and dispersion of deforested surfaces. The highest average annual decrease of forested areas was recorded in 2007 and 2012 due to the growing number of legally and illegally exploited. The results confirm that fractal analysis can provide important information on the space-time patterns of deforestation and reforestation that shows a continuous reduction.

Key words: *deforested areas, forest fund, territorial management, fractal analysis, lacunarity.*

Introduction

Monitoring the evolution of forest areas is particularly important because any intervention on this ecosystem can have negative consequences both at the level of the forest ecosystem, as well as at the level of the territorial systems based on forest exploitation. Identifying the causes underlying such changes becomes an obvious concern both for researchers, as well as for the policy makers who should develop effective management strategies adapted to territorial reality.

Fractal analysis is one way by which we can monitor the space-time evolution of forest areas, providing additional information that can be integrated into the management plans concerning the organisation and management of forest areas. The Fractal Fragmentation Index (FFI) plays an important role in quantifying the evolution of the degree of fragmentation of forested areas, showing how and how much they are spatially fragmented by deforestation. Fixed Grid 2D Lacunarity (ΛFG2DL) and Tug-of-War lacunarity (ΛT-o-W) are very useful methods for quantifying the degree of spatial homogeneity or heterogeneity of forested, deforested and reforested areas, providing valuable information on the dispersion of deforestation.

Human imprint is adversely evident in the landscape of forest ecosystems (Zelenakova and Jakubikova, 2010). One of the most important such ecosystems is the forest. By means of the area, it covers, estimated by the UN, 1/3 of the Earth's surface and is home to more than 50 % of the terrestrial species (UNEP). Furthermore, at the global level, forest areas play an important role in the circuit of chemicals in nature (Kolström et al. 2011). The existence of this ecosystem brings enormous benefits to human society, both in terms of protecting the environment and mitigating climate changes, as well as economically and socially (Galas et al., 2015; Zelenakova and Zvijakova, 2016). The benefits of forest areas are obvious, as they are subject to increased anthropogenic pressure (Mertens et al., 2000; Fearnside, 2008; Pattanayak et al., 2010; Meyfroidt et al., 2013).

The current trend shows that climate changes influence and will influence human activity and biodiversity, by amplifying the negative effects (Pachauri and Reisinger, 2007; Pachauri and Meyer, 2014). It is known that, at the global level, the proportion of greenhouse gases has dramatically increased, exceeding previous forecasts and substantial increases being forecasted for the future (Solomon et al. 2009). In protecting the environment, the forest plays a vital role in mitigating such effects generated by climate changes (increase of CO_2 due to the expansion of deforested areas, increase the proportion of greenhouse gases) (Thomas et al., 2004; Foley et al., 2005; Spittlehouse, 2005; Streck and Scholz, 2006; Betts et al., 2007; McKinley et al., 2011). Consequently, the

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increase of the deforested areas has a strong negative impact on climate parameters, with adverse effects on ecosystems that depend on the existence of the forest.

Other issues related to expansion of deforested areas are represented by the loss of biodiversity and the occurrence of hydrological hazards (amplification of erosion, floods, landslides) (Dymond et al., 2006; Bradshaw et al., 2007; Whitehead, 2011; Zanini et al., 2014; Rudel et al., 2016; Blistanova et al., 2016; Benchimol et al., 2017; Borrelli et al., 2017). Thus, it becomes obvious that reducing the deforested areas is an effective way of maintaining a satisfactory genetic diversity and a way to reduce the frequency and scale of hydrological risks.

Exploitation of forest areas causes an overburdening of forest ecosystems for the purpose of obtaining farmland (Sasaki, 2006; Porter-Bolland et al., 2012; Lopez-Angarita et al., 2016; Onyekuru and Marchant, 2016). Therefore, the use of lands and the changes to which the forest fund is subject to, are major concerns for policy makers at European and global level (van Vilet et al., 2012). In this regard, monitoring the evolution of the forest areas becomes particularly important, several methods are being used: analysis of satellite imagery (Remote sensing data analysis) (Malhi et al., 2002; Hansen et al., 2013; Beaudoin et al., 2016; Borrelli et al., 2017) and fractal analysis (Andronache et al., 2016; Blistan, 2016; Pintilii et al., 2016).

In Europe, the transformation of the natural environment by the expansion of the deforested areas is due to the demand for wood for construction and fuel (Kaplan et al., 2009; Stângă and Niacșu, 2016). The total area of forests in Romania is of 27.5 % (below the EU average of 41 %), the mountainous area being the one to hold the largest areas (59.7 %) (Report on the State of Romania's Forests, 2015).

By using fractal analysis, in this study, we followed the spatial-temporal evolution of forest areas in the mountainous area of Romania, particularly, the Northern Carpathian Mountains. Fractal dimension is very useful in estimating the irregularity or roughness of the fractal and natural objects that do not comply with the classical geometry, measuring how much space is occupied. Lacunarity completes the fractal dimension with its capacity to quantify the way in which space is occupied. Furthermore, lacunarity also discriminates the spatial distribution of gaps in texture, at multiple scales, and is not sensitive to image boundaries. In general, a greater dispersion of gap sizes in the texture of the captured image generates a greater value of lacunarity and vice versa (Reiss et al. 2016). There are several forms of determining lacunarity, such as fixed-grid algorithm (Karperien 2017), the gliding-box algorithm (Allain and Cloitre 1991), mass-related distribution algorithm, (Sengupta and Vinoy 2006), the Tug-of-War algorithm (Reiss et al. 2016). FFI (Reiss et al. 2016) complements the information obtained by lacunarity, determining the degree of compaction/fragmentation of the fractal objects analysed.

2. Materials and Methods

2.1. Study area

The area studied is located in the northern part of Romania, being a subunit of the Northern Carpathian Mountains (Fig. 1).

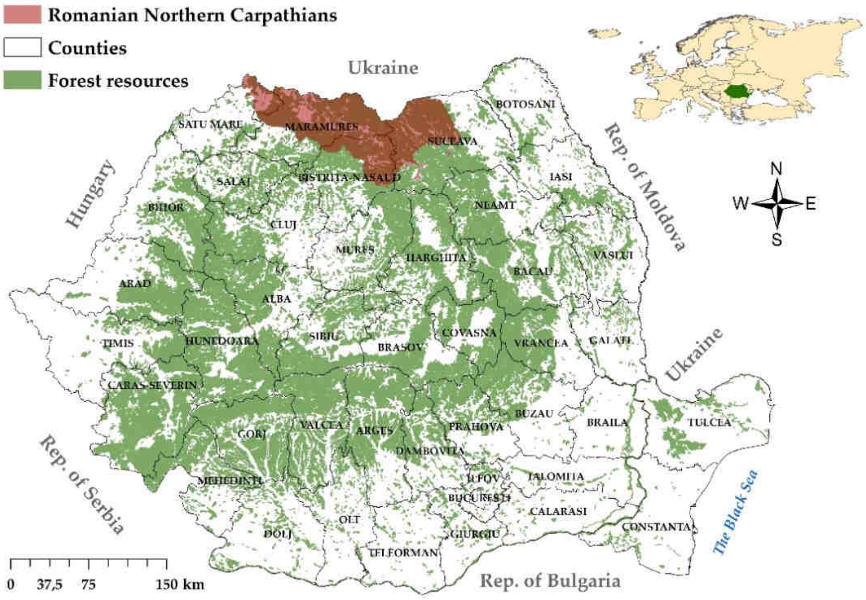

Fig. 1. Geographical position of Romanian Northern Carpathian Mountains.

This mountain subunit is totally or partially overlapped by two of the most affected counties in Romania, in terms of the deforested areas: Maramureș and Suceava (Pintilii et al., 2016; Drăghici et al., 2016; Pintilii et al., 2017). In the present study, by using fractal analysis, we have followed the space-time evolution of forest areas, during the period 2000-2014.

The deforestation is predominant in areas with flysch rocks and not a very high declivity due to the high costs of the exploitation, in Oaș-Gutâi Mountains.

In various sectors of the Eastern Carpathians some characteristics of vegetation - a variety of vertical zonality related to differences in climate, geological structure (in particular lithological) and relief massifs - could be observed (Fig. 2).

The crystalline massifs of Maramureș and Bistrița Mountains, siliceous rocks on the surface, spruce is predominant, so it meets very good conditions for growth. Only in open limestone rocks massifs, with dominant spruce, this appears with beech. Flysch massifs the Spruce is abundant in siliceous rocks, and in Rarău Mountains, made up by the conglomerate, containing limestone, the beech is in a significant proportion (Romania's geographical Monograph, 1960).

In Oaș and Gutâi volcanic mountains, beech forests are spread with conifers, and mountain meadows and the compact spruces cover the tops of these mountains.

The rocky meadows present a great development and variety of limestone rocks in alpine and mountain areas and on calcareous rocks, are various common species of Festuca.

In communities with siliceous debris from alpine areas are specific plants such as: Geum reptans, Doronicum carpaticum and on calcarous debris, plants grow, as Papaver pyrenaicum, Saxifraga moschata, Linaria alpine (Geography of Romania, 1983).

The swamps (oligotrofe marshes) are scattered on siliceous rocks (crystalline schists, eruptive, sandstones, silts). The coppices develop on meadows on alluvial deposits (gravels, sands, clays). The riparian forests are made up of poplar (Populus), willow (Salix), alder (Alnus) and are also located in boreal and hardwood forests, being an intra-zone vegetation. The coppices from mountains are made of white alder (Alnus incana) and in a small proportion the spruce (Picea) and fir (Abies).

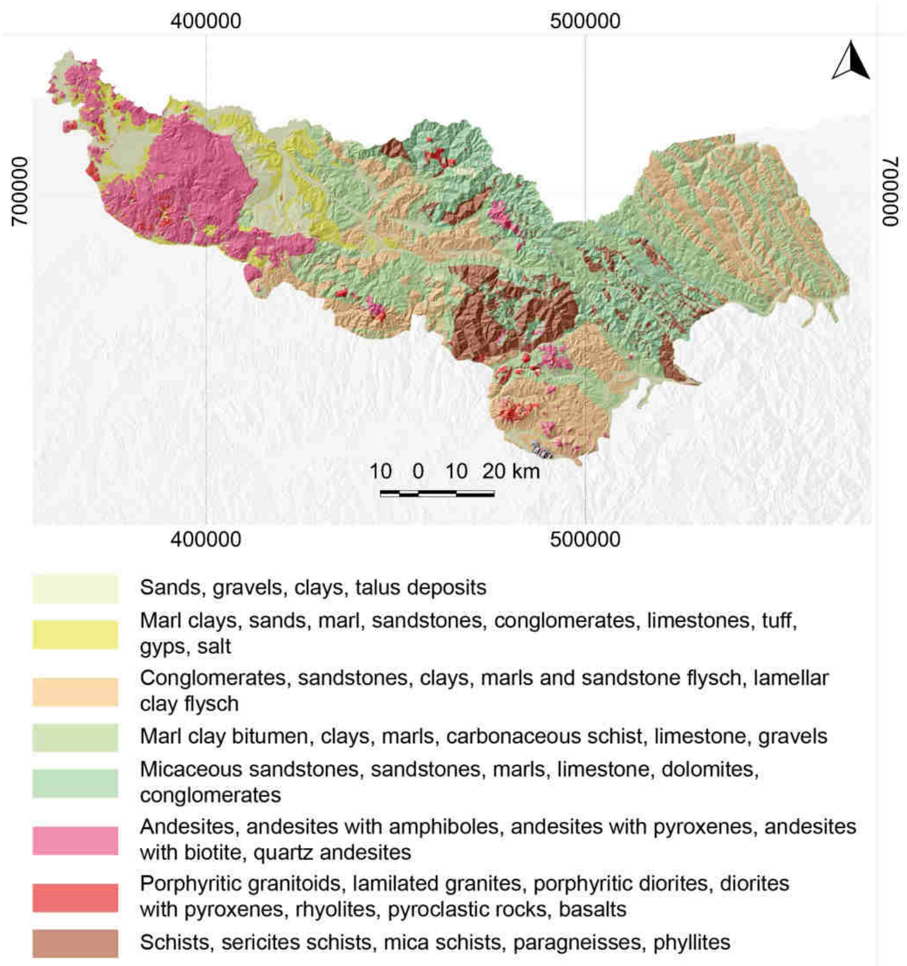

Fig. 2. Geological map of Romanian Northern Carpathian Mountains.

2.2 Image preprocessing

To assess the forested, deforested and reforested areas, the global database provided by the Department of Geographical Sciences, Maryland University, was used. The database shows the evolution of the forest areas at the global level, in the period 2000-2014, being the result of the analysis of 654178 Landsat 7 ETM + (Hansen et al. 2013). By using ArcGIS, the forested, deforested and reforested areas were extracted in TIFF format. The resolution 3020x1590 pixels was chosen (214.92x112,182 km). In order to be fractally analysed, TIFF images were manually binarised using ImageJ 1.51i (Ruifrok and Johnston 2001). Based on the binarised TIFF images, forested, deforested and reforested areas were determined using the following macro in ImageJ:

```
// this macro measures the area and the percentage of the foreground (forest) pixels in 8-bit binary image from Northern Group of the Eastern Carpathians
dir = getDirectory("path");
list = getFileList(dir);
for (i=0; i<list.length; i++)
{
  if (endsWith(list[i], ".tif"))
  {
      open(dir + list[i]);
      run("8-bit");
setAutoThreshold("Default");
  // change scale from inches to km (for scale 1:550.000)
  run("Set Scale...", "distance=14.0933 known=1 pixel=1 unit=km");
  // measure area and area fraction
  run("Set Measurements...", "area area_fraction limit display redirect=None decimal=3");
  run("Measure");
  selectWindow("Results");
      close();
   }
}
```

2.3 Fractal Analysing

According to the same binary TIFF images, also the evolution of the degree of fragmentation/compaction and heterogeneity/homogeneity of forested, deforested and reforested areas in Romania was determined for the period 2000-2014, by using: Fractal Fragmentation Index (https://sourceforge.net/projects/iqm-plugin-ffi/), Fixed Grid 2D Lacunarity and Tug-of-War Lacunarity (which is a fast and efficient method for the processing of high-resolution images). IQM 3.2 software was used (Kainz et al. 2015).

Fractal Fragmentation Index quantifies in a single value the information obtained from fractal analysis on mass-concentration, but also of the tortuosity of the perimeters, thus describing the fractal fragmentation, and can, therefore, be also interpreted as compaction index (Reiss et al. 2016). It was determined by using FFI plugin (Ahammer and Andronache 2017).

$$FFI = D_{B-C}A - D_{B-C}P \qquad (1)$$

where FFI is the fractal fragmentation index, $D_{B-C}A$ is the fractal dimension of the summed up areas and $D_{B-C}P$ is the fractal dimension of the summed up perimeters.

According to Reiss et al. 2016 FFI = 0, when $D_{B-C}A = D_{B-C}P$, meaning that the forested areas are represented only in very small, point-like areas. The closer FFI is to 0, the more fragmented, more dispersed, smaller and fewer or tentacular and sprawling patterned the forested areas are. The closer FFI is to 1, the larger and more compact the forested areas are, being disposed in clusters.

FFI = 1 is recorded only when the afforested areas are geometrically perfect and 100 % compact, without any discontinuity ($D_{B-C}P = 1$ and $D_{B-C}A = 2$).

$D_{B-C}A$ and $D_{B-C}P$ were obtained by using the Box-Counting algorithm (Reiss et al. 2016).

Fixed Grid 2D Lacunarity ($\boldsymbol{\Lambda_{FG2DL}}$) was used to calculate the degree of heterogeneity by the variation of deforested areas distribution and it is determined using the following equation:

$$(\boldsymbol{\Lambda_{FG2DL}}) = (\boldsymbol{CV_{FG2DL}})^2 \qquad (2)$$

where $\boldsymbol{CV_{FG2DL}}$ is the coefficient of variation (Karperien 1999-2013). The higher the Λ_{FG2DL} value, the more heterogeneous and chaotically done the deforestation is, and vice-versa.

Tug-of-War lacunarity and for additional information on the degree of fragmentation/compaction of poor regions, the Fractal Fragmentation Index (FFI) was used. Tug-of-War lacunarity ($\Lambda_{\mathrm{T-o-W}}$) was determined by using plugin frac2D (Reiss 2016).

($\Lambda_{\mathrm{T-o-W}}$) algorithm which allows for the estimation of lacunarity in one single pass over the image, by using only a small and constant quantity of memory and, at the same time offers values very close to gliding-box (Reiss et al. 2016).

($\Lambda_{\mathrm{T-o-W}}$) is calculated according to the equation:

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

N(r) = number of boxes

Z2 = the second moment for each width as the median of s2 values, each of which is the mean of s1 squares of the counter values.

s1 and s2 are two predefined parameters indicating the accuracy and reliability

$L^2 \approx \left(\sum_{i=1}^{N(r)} p\,(r,i)\right)^2$, where p(r, i) is the number of occupied sides in the i-th box.

3. Results

3.1 Forested, deforested and reforested areas

Evolution of forested area in the Eastern Carpathians show a general downward trend as a result of the increasingly more pronounced logging, both legal and illegal, decrease influenced by the economic changes undertaken during this period and the legislative changes that have encouraged deforestation (Fig. 2).

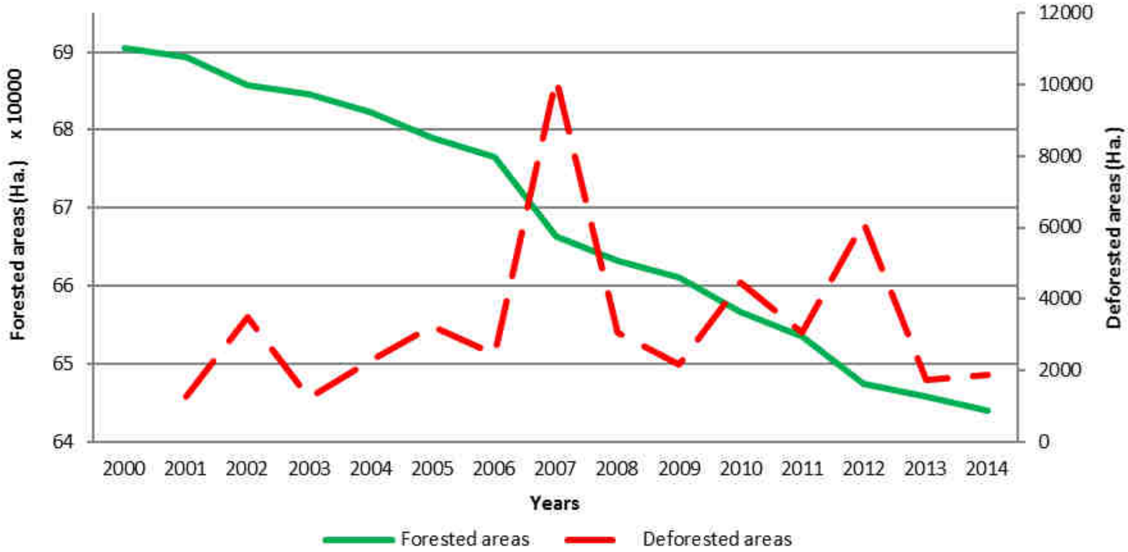

Fig. 2. Evolution of the forested area in the Northern Carpathian Mountains of Romania, in the period 2000-2014.

Forest areas have continuously decreased, year after year, but not in a constant rhythm, reaching in 2014, 643,932.6 ha. (Fig. 3). In 2007 and 2012, the largest average annual decreases were recorded, the lowest being recorded in 2001 and 2003, just as in the case of the deforestation in Maramureș (Pintilii et al., 2017).

In total, 46,995.5 hectares were deforested, the forest area being reduced during 2000-2014 by 6.75 %. During this time interval, only 20,131.3 ha were reforested, a very large deficit of 57.2 % being created.

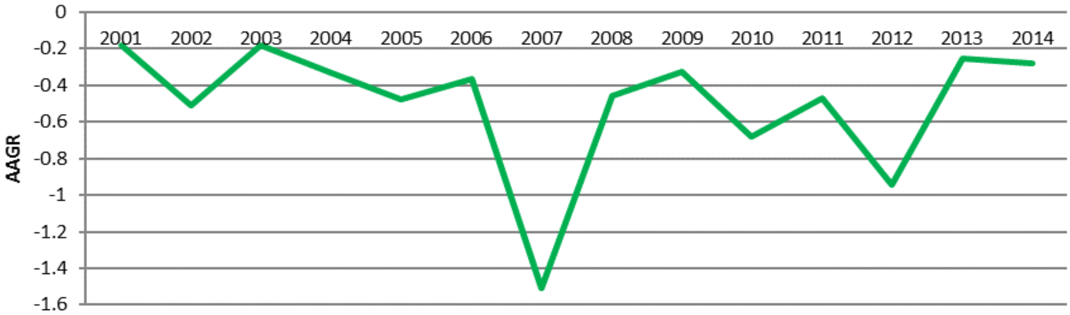

Fig. 3. Average Annual Growth Rate of forested areas in the Northern Carpathian Mountains of Romania, during the period 2000-2014.

If y 2004 deforestation was dispersed in small patches by 2004, a clustering process is manifested (Fig. 4) by the creation of clusters in Maramureș and Rodna Mountains since 2005. This coincides with an increasingly more pronounced declustering of the forested areas.

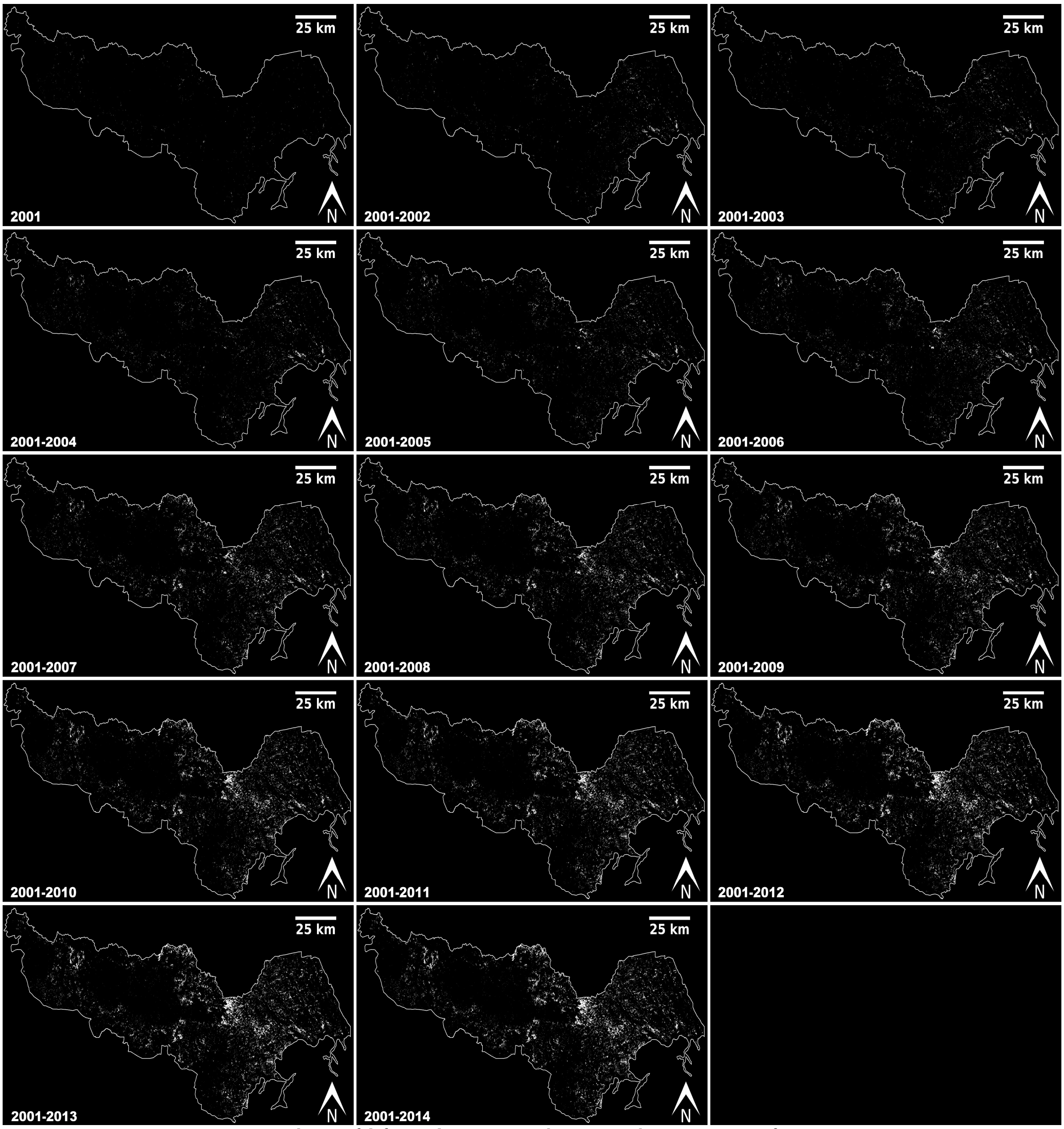

Fig. 4. Evolution of deforested areas in Northern Carpathian Mountains of Romania.

3.2 Fractal Fragmentation Index (FFI)

Low FFI values, below 0.15, indicate that Northern Carpathian Mountains of Romania have a great fragmentation of the forest area (Fig. 5). As the deforestation extended during the period under review, FFI of the afforested areas of the Northern Carpathian Mountains of Romania (Fig. 5) decreased by 0.04, from 0.15 (2000) to 0.11 (2014) indicating a continuous growth of the fragmentation of the afforested areas, particularly in Rodna, Maramureș and Obcina Mestecăniș Mountains, where there is a process of declustering. The largest decrease of FFI was recorded in 2007 (0.007) against the escalating deforestation carried out. The lowest decrease of FFI occurred in 2013-2014 (0.001) when small forest areas were deforested (1739 ha, respectively, 1871.4 ha).

Deforestation carried out dominantly fragmented makes FFI to be encompassed between 0.001 and 0.007. More compact deforestation (>0.005) occurred in 2002, 2005 and 2007, while fragmented deforestation (<0.002) were recorded in 2001 and 2003.

As regards the summation of deforested areas, since 2005, a trend of increasing the compaction by clustering of deforestation (Fig. 5) from 0.005 to 0.015, can be observed.

FFI of the reforested area for the period 2001-2014 was very low, of 0.004, being by 0.1 lower than that of the deforested area, indicating that the regeneration was carried out much less compact than deforestation.

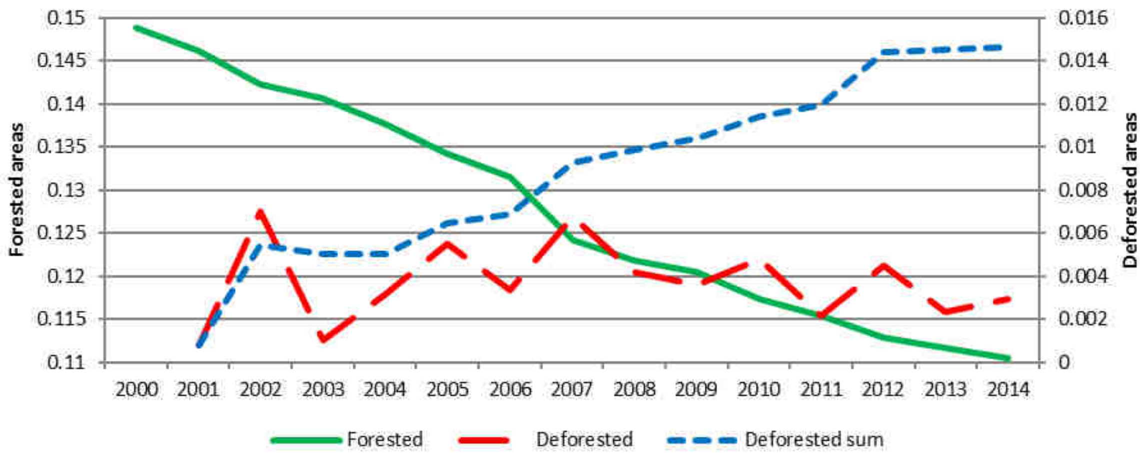

Fig. 5. Evolution of the Fractal Fragmentation Index (FFI).

3.3 Evolution of the Fixed Grid 2D Lacunarity (Λ_{FG2DL})

The use of Λ_{FG2DL} allowed us to quantify the degree of heterogeneity of forest areas, highlighting how homogeneous or heterogeneous deforestation was carried out. Against deforestation, the lacunarity of the forest area increased, Λ_{FG2DL} by 0.01 from 0.14 in 2000 to 0.15 in 2014 (Fig. 6).

In terms of the deforested area, the most heterogeneous deforestation was carried out when they were fragmented, that is, in 2001 and 2003 ($\Lambda_{FG2DL} > 1$), while the most homogeneous deforestation was performed when they were larger and more compact ($\Lambda_{FG2DL} < 0.85$), in 2002, 2007, 2010 and 2012.

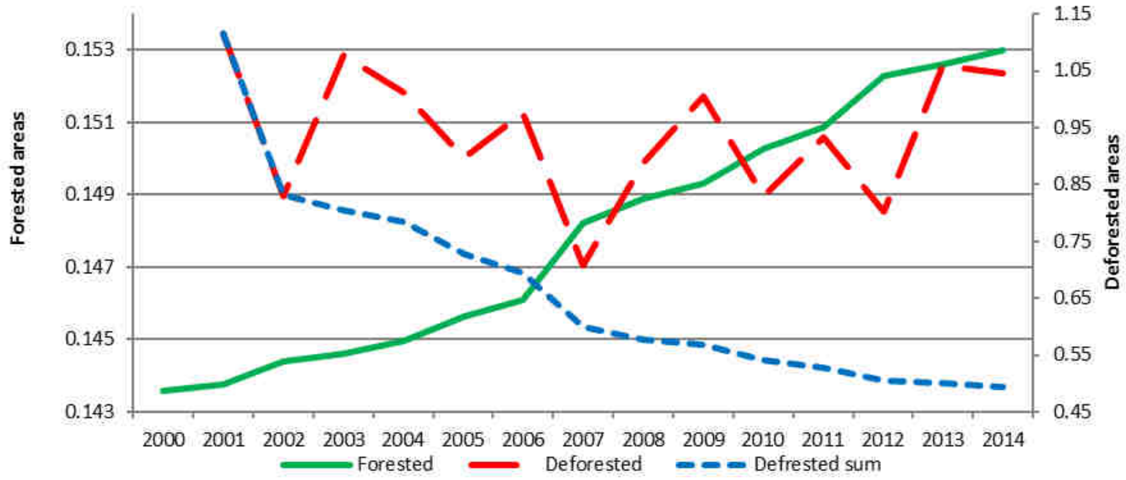

Fig. 6. Evolution of the Fixed Grid 2D Lacunarity (Λ_{FG2DL}).

Regarding the summation of the deforested areas, there is a noticeable downward trend of heterogeneity by the clustering of deforestation (Fig. 5) from 1.12 to 0.49.

$\boldsymbol{\Lambda_{FG2DL}}$of the reforested surface for the period 2001-2014 was greater (0.61) than that of the deforested area (0.49), which indicates that the regeneration was made much more heterogeneously than deforestation.

3.4 Tug of War Lacunarity ($\boldsymbol{\Lambda_{T-o-W}}$)

The use of Λ_{T-o-W} allowed us to quantify, by another algorithm, the degree of heterogeneity of forest areas. In terms of the forested areas, Λ_{T-o-W} has captured the local effects of deforestation on the compaction of forested areas. Thus, in the years of more homogeneous, compact and intense deforestation (2007, 2010), Λ_{T-o-W} emphasised the declustering process, and in the years of more heterogeneous, fragmented deforestation (2004, 2013, 2014), it had limited effects on the declustering of forested areas.

In terms of the Λ_{T-o-W} analysis of deforested areas, there was a strong correlation with Λ_{FG2DL} (R^2=0.97).

Lacunarity of forest area increased against deforestation, Λ_{FG2DL} by 0.01, from 0.14 in 2000 to 0.15 in 2014 (Fig. 6).

As regards the deforested areas, the most heterogeneous deforestation was carried out when they were fragmented, that is in 2001 and 2003 (Λ_{FG2DL}>1), when the most homogeneous deforestation was carried out when they were greater and more compact (Λ_{FG2DL}<0.85), in 2002, 2007, 2010 and 2012.

In terms of the summation of the deforested areas, a decrease of heterogeneity can be observed by the clustering of deforestation (Fig. 5) from 1.12 to 0.49.

Λ_{T-o-W} of the reforested area for the period 2001-2014, just as in the Λ_{FG2DL} case, was higher (0.6) than of the deforested area (0.51), which confirms that the regeneration was done much more heterogeneously than the deforestation.

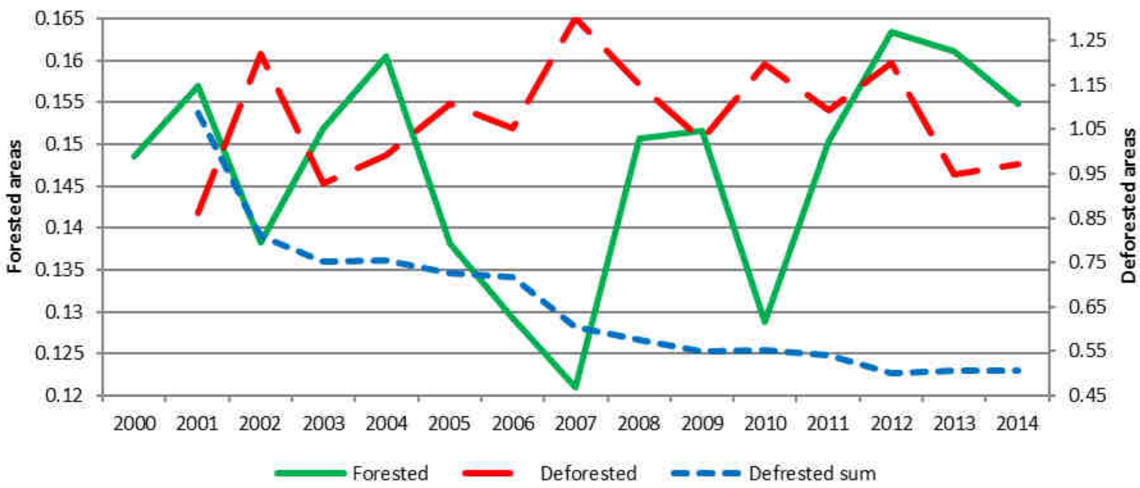

Fig. 7. Evolution of T-o-W lacunarity (Λ_{T-o-W}).

4. Discussion

The evolution of forested areas in the Northern Group of the Eastern Carpathians shows a continuous reduction, year by year, but inconsistent as rhythmicity. In 2007 and 2012, the highest average annual decrease of forested areas was recorded, against the growing number of legally and illegally exploited forest areas. Such decrease is mainly due to policies regarding the exploitation of the forest fund reflected in legislative changes in the field (Report on the State of Romania's Forests, 2015) but also the economic changes of the past 15 years (Pintilii et al., 2015; Andronache et al., 2016; Ciobotaru et al., 2016; Pintilii et al., 2017).

In the case studym, we have used fractal analysis to study the space-time evolution of the forest areas, following the degree of heterogeneity and the dispersion of the deforested areas by Fixed Grid 2D Lacunarity (Pintilii et. al, 2017) and Λ_{T-o-W} (Reiss et al., 2016; Ciobotaru et. Al, 2016), as well as the fragmentation of forested areas affected by deforestation, by FFI (Andronache et al., 2016), using the Box-Counting method (Russel et al., 1980; Sun and Southworth, 2013).

FFI index used to determine the fragmentation/compaction of forests at county level (Andronache et al., 2016), or at TAUs level (Pintilii et al., 2017) was analysed for the Eastern Carpathians – the Northern Group for a period of 15 years, in order to determine the degree of clustering of areas under forests.

Compared to previous studies that have used $\Lambda_{Sengupta-Vinoy}$ (Andronache et al., 2016; Pintiliii et al., 2016), or Λ_{FG2DL} (Pintilii et al., 2017) analyses, in this study, we addressed a different method for determining the lacunarity: Λ_{T-o-W}. Our study showed that both $\Lambda_{Sengupta-Vinoy}$ and Λ_{FG2DL} can be valuable complementary tools in quantifying the degree of spatial homogeneity or heterogeneity or the forested, deforested and reforested areas, providing new quantitative information on their dispersion.

Through our research, we have shown that:

- Forested areas have decreased in size, but inconsistently, as the Average Annual Growth Rate.
- The existence of a clustering trend of deforestation (by increased compaction and homogenization), against their expansion, especially after 2005.
- Regeneration was carried out much more heterogeneously and fragmented than deforestation Λ_{FG2DL}, and Λ_{T-o-W} of the reforested area was higher than of the deforested area.

Λ_{T-o-W} captured the local effects of deforestation on the compaction of forested areas. In this respect, we have shown that in the years of more homogeneous, compact and intense deforestation, Λ_{T-o-W} indicated that deforestation had emphasised the declustering of forested areas. In the years with a more heterogeneous, fragmented deforestation, Λ_{T-o-W} indicated that deforestation had limited effects on the declustering of forested areas.

5. Conclusion

Monitoring the evolution of forest areas is particularly important since any intervention on this ecosystem can have negative consequences, both at the level of the forest ecosystem, as well as at the level of territorial systems based on forest exploitation. Identifying the causes underlying such transformations becomes an obvious concern both for researchers, as well as for the policy makers who should develop effective management strategies adapted to territorial reality.

Fractal analysis is one of the ways by which we can follow the space-time evolution of forest areas, providing additional information that can be integrated into the management plans concerning the organisation and the management of forested areas. FFI plays an important role in quantifying the evolution of the degree of fragmentation of forested areas, indicating how and how much it is spatially fragmented by deforestation. Λ_{FG2DL} and Λ_{T-o-W} are very useful methods for quantifying the degree of spatial homogeneity or heterogeneity of forested, deforested and reforested areas, providing valuable information on the dispersion of deforestation.

Our research confirms the hypothesis that the fractal analysis of Landsat imagery in 30 m resolutions provides valuable quantitative information on the space-time patterns of deforestation and regeneration. Thus, through fractal analysis, we obtained complementary information on deforestation and regeneration, compared to the classic detection analyses based on changes in image classification, as fractal analysis is able to analyse irregular spatial structures.

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