ASSESSING LANDSCAPE FRAGMENTATION DYNAMICS WITH FOURIER TRANSFORMS

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ABSTRACT

Quantifying landscape fragmentation is crucial for understanding its impact on biodiversity. Within landscape ecology, there is an ongoing effort to create metrics that systematically characterize landscape patterns and predict their effects on various species. In this study, we utilized Fourier transforms to measure landscape fragmentation in urban and heterogeneous landscapes over periods of 24 and 12 years, respectively. Analyzing Landsat images from 1986, 1999, and 2010, we focused on the first principal component (PC1) to evaluate changes in fragmentation over time. Our analysis revealed a significant increase in fragmentation in urban areas from 1986 to 2010, with a particularly noticeable rise between 1999 and 2010. Specifically, the average Fourier spectrum decreased slightly from 16.0 to 15.9 throughout the study period, indicating increased fragmentation at both urban and landscape levels. The sensitivity analysis further showed that removing 6,000 cells from the original image caused the mean Fourier spectrum to drop from 16.0 to 15.5, demonstrating the method's effectiveness in detecting subtle land cover changes. Our findings demonstrated that Fourier analysis effectively detects subtle landscape changes, particularly in larger study areas and over longer time intervals. However, it lacks detailed information on specific types or quantities of altered land cover. To address this limitation, integrating Fourier analysis with land cover classification datasets could enhance understanding of landscape dynamics and support more informed conservation and management decisions.

Keywords: Fourier analysis, landscape ecology, urban pattern changes, landscape fragmentation.

INTRODUCTION

Landscape ecologists not only focus on the landscape structure but also its changes (Gustafson 1998). The structure and dynamics of landscapes can be studied using either continuous or discrete heterogeneity models (Rahimi *et al.*, 2022). Many approaches assume that landscapes consist of discrete objects or patches belonging to specific layers or systemic conditions). Such discrete representations of landscapes are abundant and useful for simplifying and reducing the complexity of landscapes. The discrete representation of landscapes has been highly successful in a wide range of landscape ecology topics (McGarigal & Cushman, 2005; McGarigal *et al.*, 2009). Landscape ecology defines fragmentation as the subdivision of habitats, ecosystems, and land uses into smaller components (Fahrig, 2003). Therefore, fragmentation may be considered a physical process leading to habitat loss, reduction in habitat size, or increased isolation of habitat patches (Fahrig, 2017). One of the significant issues addressed by landscape ecology is the interaction between landscape patterns and fundamental ecological processes (Turner, 1990; Turner *et al*., 2003; Uuemaa *et al*., 2009; Fu *et al*., 2011). Therefore, a quantitative description of spatial patterns is a crucial step in understanding this interaction (Buyantuyev & Wu, 2010; Luck & Wu, 2002; Rahimi *et al*., 2021; Turner, 1990).

Landscape ecology strives to develop metrics systematically describing landscape patterns and predicting the effects of pattern changes on different species (Burel, 2003; Farina, 2006; Riitters *et al*., 1995; Naveh & Lieberman, 2013). Remote sensing, coupled with landscape pattern analysis, provides a framework for measuring and studying landscape structure. Landscape pattern analysis based on remote sensing data plays a crucial role in detecting fragmentation. This analysis is primarily conducted using land cover maps derived from remote sensing data (Crowley & Cardille, 2020). However, it also poses some challenges (Castilla & Hay, 2007; Valle *et al*., 2023; Cheng *et al*., 2021), including (1) implicit reduction of informational content, (2) decreased continuous information about fragmentation processes, and (3) issues related to the classification of satellite images with different spatial resolutions (33). Recently, landscape ecology studies have paid more attention to continuous approaches for measuring landscape fragmentation (Rahimi *et al*., 2021, 2022; Qiu *et al*., 2021; Smith *et al*., 2021; Lizarazo, 2012). Alternative approaches based on continuous information, previously used for detecting landscape changes such as fragmentation, include fuzzy set theory (Lizarazo, 2012), spectral unmixing (Michishita *et al*., 2012), texture-based metrics (Park & Guldmann, 2020), surface metrics(McGarigal *et al*., 2009), spatial autocorrelation indices (Fan & Myint, 2014), and Fourier analysis (Rocchini *et al*., 2013).

The utilization of Fourier analysis in landscape studies was first introduced by Rocchini *et al*. (2013) to examine landscape fragmentation using satellite images at different time intervals. The results of this study indicated a significant increase in the density of Fourier spectrum values over 15 years, affirming Fourier analysis's capability in detecting landscape fragmentation across different periods (Rocchini *et al*., 2013). Wieland & Dalchow (2009) employed Fourier analysis to detect landform shapes. The results of their study demonstrated that Fourier analysis effectively identifies fundamental landscape structures such as depressions and elevations. Singh *et al*., (2014) also estimated ground-level forest biomass using principal component analysis and Fourier analysis. The results showed that this combined method accurately assigns biomass values to different forest types, aligning with field measurements. Kareem (2008) utilized Fourier analysis to create dimensionality-reduced landscape patterns, indicating its efficiency and usefulness in generating such landscape patterns.

Lundquist & Sommerfeld (2002) used Fourier analysis to define landscape scales in analyzing disturbances present in forest areas. They aimed to classify forest gaps using Fourier analysis as their primary research objective, and their results highlighted the usefulness of Fourier analysis in assessing canopy structure and spatial pattern quantification. Rockmore *et al*. (2002) also employed Fourier analysis in determining landscape suitability, with their study results indicating Fourier analysis's effectiveness in identifying suitable landscapes. Couteron *et al*., (2006) compared and analyzed landscape patterns based on Fourier spectral analysis, acknowledging that spectral analysis based on Fourier analysis is a powerful tool for identifying prominent scales of landscape patterns and comparing them with each other.

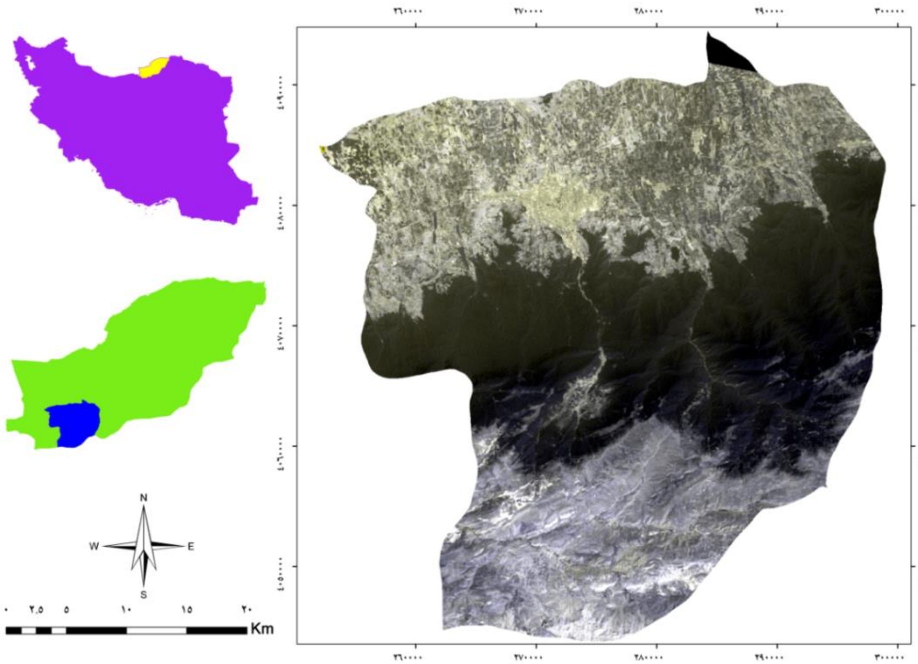
Despite studies highlighting the effectiveness of Fourier transforms in analyzing various aspects of surface imagery and demonstrating its efficacy, significant questions remain regarding their application in scrutinizing incremental changes in the landscapes. For instance, while this method is typically utilized across two temporal periods to assess changes within the same landscape, the optimal duration of these periods for sensitivity to these transformations remains unclear. Moreover, it's uncertain whether the method's effectiveness varies across different regions, such as rural, urban, or otherwise. Additionally, the sensitivity of this method to changes in specific features like topography requires further investigation through sensitivity testing to ascertain its efficacy in detecting subtle changes. The objectives of this study are as follows: 1. To identify and determine the efficiency of the Fourier analysis approach in quantifying heterogeneous changes in landscape and urban patterns of Gorgan County, Iran, over 24 years. 2. To evaluate the strengths and weaknesses of the Fourier analysis approach in capturing landscape and urban transformation. 3. To conduct a sensitivity analysis to assess the responsiveness of this method to minor alterations in landscape and urban patterns.

METHODS

Study Area

The Gorgan County, located in Golestan province, spans from approximately 10°54' to 45°54' east longitude and 44°36' to 58°36' north latitude, covering an area of roughly 1316 square kilometers (Fig. 1). This region is geographically diverse, with the southern part characterized by forest-covered mountains, while the northern section lies adjacent to the national highway.

Fig. 1: The location of the study area in Iran and Golestan province (Landsat satellite image, 2010)



Gorgan's climate is classified as moderately humid, contributing to a rich and diverse ecosystem. The average slope of the area is 27 percent, indicative of its varied terrain. However, recent studies have highlighted significant landscape degradation and fragmentation, driven by deforestation, urban expansion, and agricultural development, which pose ongoing challenges to environmental sustainability and biodiversity conservation in the region (Rahimi *et al*., 2016).

Data

The data used in this study include Landsat 7 Enhanced Thematic Mapper (ETM+) imagery (April 2010) and Landsat 5 Thematic Mapper (TM) imagery (April 1986 and 1999). These satellite images were utilized to investigate fragmentation changes over two periods of 24 at landscape and 12 years at city levels, covering both urban and whole landscapes of Gorgan County.

Examining landscape fragmentation changes using Fourier analysis

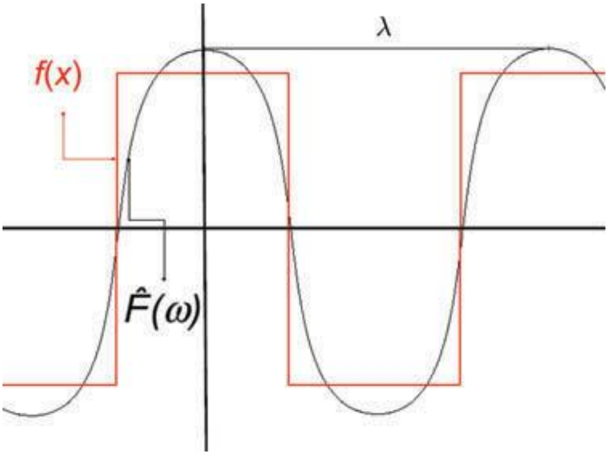
Fourier analysis, introduced by the French mathematician Joseph Fourier in 1807 to simplify complex heat transfer calculations in objects, has found widespread applications today. Fourier analysis is a mathematical approach that has been widely applied across various disciplines, including landscape ecology, to analyze spatial patterns and landscape fragmentation. This technique decomposes spatial data into a series of frequency components, allowing researchers to explore patterns at different scales. In landscape ecology, fragmentation often involves complex spatial dynamics that can vary significantly across space and time, making Fourier analysis particularly suitable for this type of investigation. Unlike traditional methods that focus on individual patches or local measures, Fourier analysis provides a broader view of landscape patterns by focusing on the distribution of spatial frequencies, thus offering a more comprehensive assessment of landscape heterogeneity.

One of the key advantages of Fourier analysis is its ability to analyze landscape patterns globally across an entire image, rather than focusing on specific patches or regions. This global approach allows for the identification of broad trends in landscape fragmentation while also revealing the finer-scale details that may emerge in more fragmented areas. By applying Fourier analysis to satellite imagery, researchers can capture a detailed, multi-scale view of landscape changes over time, making it an effective tool for long-term monitoring of environmental changes and habitat degradation. Considering f (x) as a continuous function within a spatial domain, according to Fourier theory, every f(x) can be transformed into a series of sinusoidal functions with different frequencies (Equation 1).

$$F\ (\omega) = \int_{-\infty}^{+\infty} f\ (x)\, e^{-2\pi i\omega\omega} dx$$

Where ω represents the frequency, which is also known as the radian frequency or angular frequency (Fig. 2). Extending Equation 1 to two dimensions (Equation 2) implies considering a two-dimensional function such as a raster matrix f(x,y) (Fig. 3). Therefore, its Fourier transform will be as follows.

Fig. 2: According to Fourier theory, a continuous function can be transformed into a series of sinusoidal functions with different frequencies

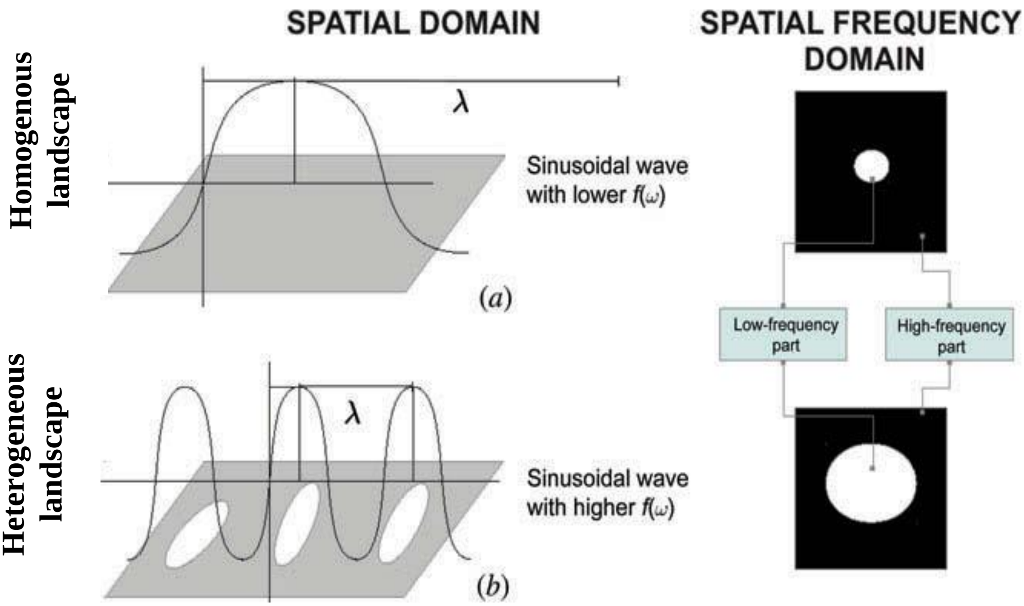


$$F\ (\omega, v) = \iint_{-\infty}^{+\infty} f\ (x, y)\, e^{-2\pi i(\omega x + v y)} dx dy$$

Where ω and v represent the frequency coordinates.

In general, when Fourier analysis is applied to satellite imagery, lower frequencies are centered in the Fourier spectrum, while higher frequencies are located around the center of this spectrum. Therefore, it is expected that images that are homogeneous or, in other words, have lower frequencies, will exhibit higher values at the center of the scatter plot ω and v, and very low values around the spectrum (Fig. 3a). An increase in fragmentation leads to an increase in higher frequencies, resulting in a more complex Fourier spectrum where higher values are in the high-frequency region of the Fourier spectrum (outer part of the spectrum) (Fig. 3-b).

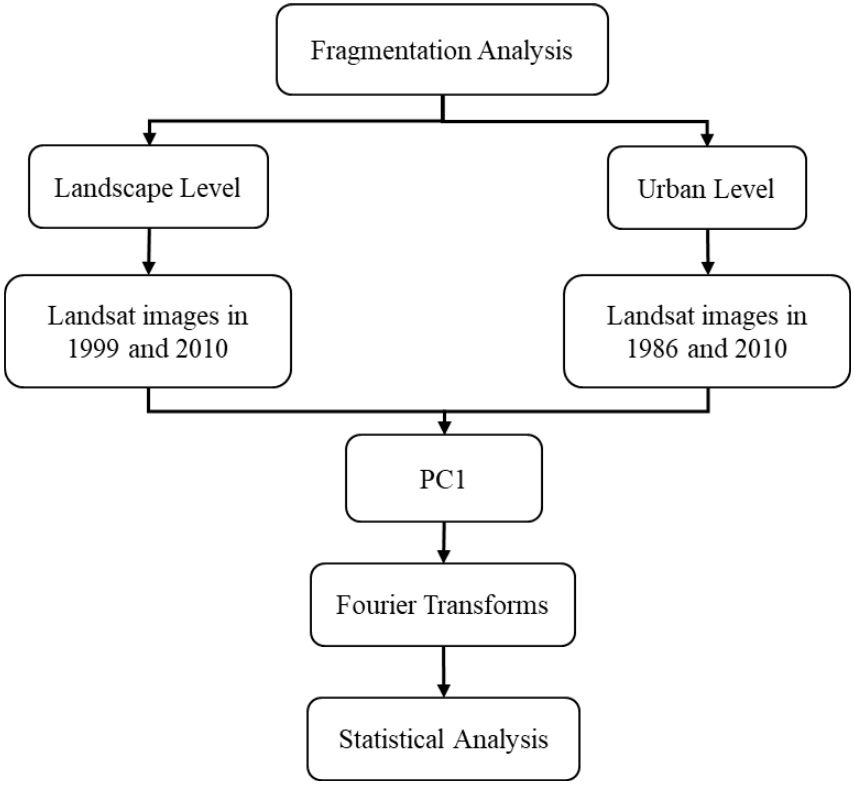
Fig. 3. Visualization of land cover patterns over time, depicting two distinct scenarios: (a) two different land cover patterns and (b) the same land cover pattern captured at different time points. In Fourier analysis, lower frequencies, which correspond to smoother and more homogeneous areas, are positioned at the center of the Fourier spectrum. In contrast, higher frequencies indicate increased fragmentation and complexity, found in the outer regions of the spectrum. As fragmentation occurs, the presence of higher frequencies rises, suggesting a more intricate landscape structure. This relationship is key for analyzing landscape changes and understanding ecological dynamics (Rocchini *et al*., 2013).



Landscape and urban fragmentation

For the analysis of fragmentation changes using Fourier analysis, IDRISI software was utilized. Since Fourier analysis is performed on a single image, Principal Component Analysis (PCA) was employed to decompose the images into their principal components. In this process, the first component contains the most information. Therefore, the first component of each Landsat image was used as input for the Fourier analysis tool. The first components of Landsat images in the years 1986, 1999, and 2010 encompassed 91 %, 86 %, and 93 % of the variance of all bands, respectively. In IDRISI software, Fourier analysis is conducted in two stages: Forward and Inverse. In the Forward stage, the image is decomposed into sinusoidal waves. The output of Fourier analysis includes three images: Real, Imaginary, and Power Spectrum. The first image represents cosine waves, the second image represents sine waves, and the third image is solely used for visualization and error correction. In this study, the third image was utilized to examine fragmentation. The trend of land cover changes was investigated over 24 years in the urban area and 12 years across the entire study area. Fig. 4 summarizes the research stages. To investigate heterogeneous changes at the urban level, a subset was extracted from the principal component, mainly covering urban areas.

Fig. 4: Steps for detecting fragmentation changes using Fourier analysis



Sensitivity Analysis

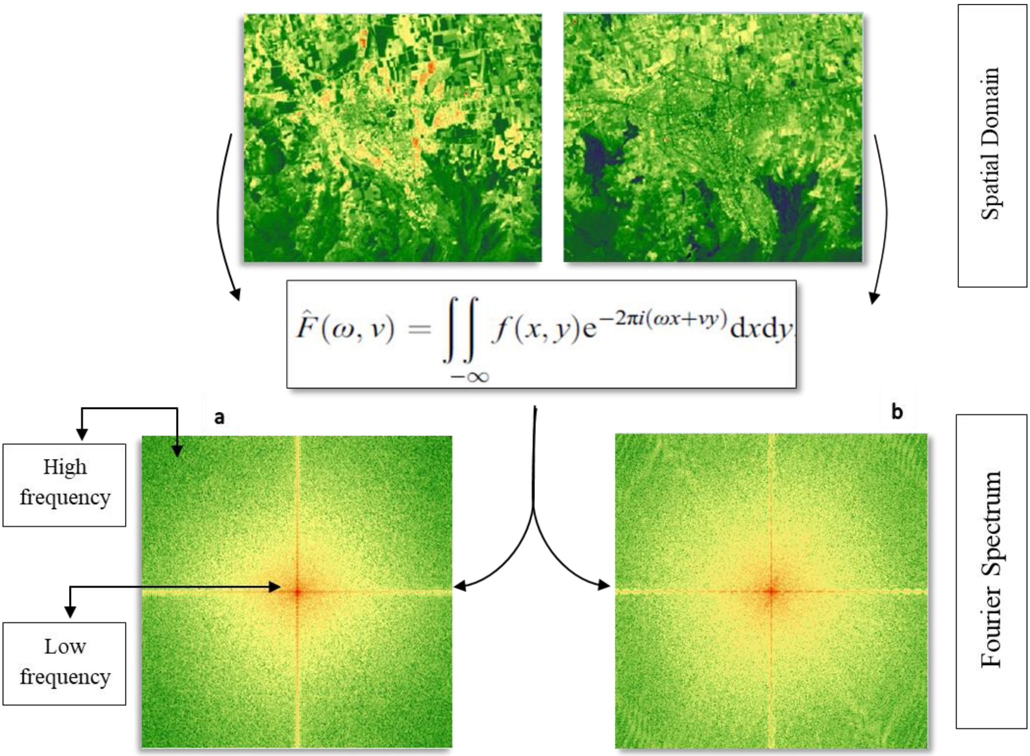
The question raised regarding Fourier analysis pertains to the sensitivity of this tool to small changes and its ability to capture minor variations. To address these inquiries, random changes were introduced using MATLAB software to the first component image at the landscape level of Gorgan County in 1389. The alteration process involved randomly selecting 200 cells at each stage of modification and converting them to zero. This procedure was repeated 30 times, leading to the removal of a total of 6,000 cells from the original input image in the final stage. Subsequently, Fourier analysis was conducted for each of these 30 modified images, and the average spectra obtained were plotted against the stages of random cell removal.

RESULTS

Fragmentation changes at the urban level

The results of the Fourier analysis on the first components of the images related to the urban area of Gorgan city were presented as the Fourier spectra (Fig. 5). The first component of the Landsat image in 1986 (a) depicted a more homogeneous image compared to the 2010 image (b), primarily due to the significant urban growth in 2010 in this area. The arrangement of values in the Fourier spectrum was such that as one moved from the center of the spectrum towards the outer part, the frequencies increased. Therefore, the higher the frequencies appearing in the outer part of the Fourier spectrum, the more heterogeneous the first components were. A comparison of the Fourier analysis outputs on the first components of the Landsat images indicated that the pattern of homogeneous frequencies in 1986 was greater than in 2010.

Fig. 5: The results of the Fourier analysis on the PC1 of Landsat images at the urban level. (a) Fourier spectrum in 1986 and (b) Fourier spectrum in 2010

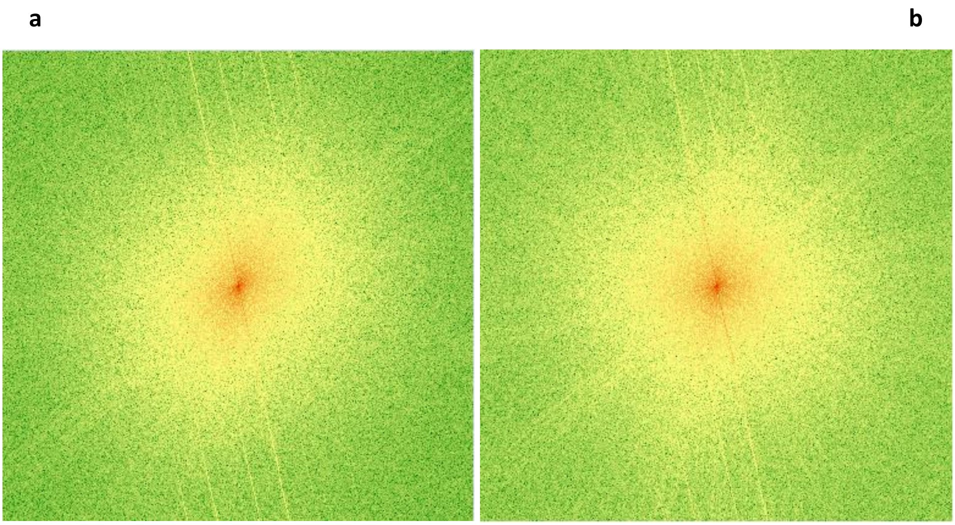


According to the discussions mentioned, homogeneous frequencies resulted from the absence of fragmentation in the area. The positioning of these homogeneous frequencies was at the center of the Fourier spectrum, meaning that the more concentrated values (light green) in the spectrum's center indicated a more homogeneous region. The dark green color dominated the Fourier spectrum of 1986, representing low values or high frequencies (outer part of the spectrum), while in the 2010 spectrum, a mixture of light and dark green colors was visible in the outer part of the spectrum. In the outer part of the 2010 Fourier spectrum, irregularities and an increase in high frequencies were observed, indicating an increase in heterogeneity in the studied area. In fact, in the outputs of the Fourier analysis in 1986, very similar values were seen in the high-frequency part of the spectrum (outer part of the Fourier spectrum), while in the 2010 output, more heterogeneity and dissimilarity were observed. This heterogeneity in the outer part of the Fourier spectrum (Figure 5-2) indicated an increase in urban fragmentation over 24 years, leading to an increase in high frequencies in this image.

Fragmentation changes at the landscape level

The results of Fourier analysis on the first components of Landsat images in the years 1999 and 2010 were presented as Fourier spectra (Fig. 6). The difference between Fig. 5 and 6 lay in the extent of the evaluated areas. In Fig. 5, only urban areas were examined, whereas the results in Fig. 6 pertained to the entire land cover of Gorgan, encompassing the city of Gorgan, agricultural fields, and surrounding forests. When an undisturbed homogeneous area was considered as the input for Fourier analysis, the output image was characterized by high values (low frequencies) centered in the Fourier spectrum, with low values (high frequencies) located in the outer part of the spectrum.

Fig. 6: The results of the Fourier analysis on the PC1 of Landsat images at the landscape level. (a) Fourier spectrum in 1999 and (b) Fourier spectrum in 2010



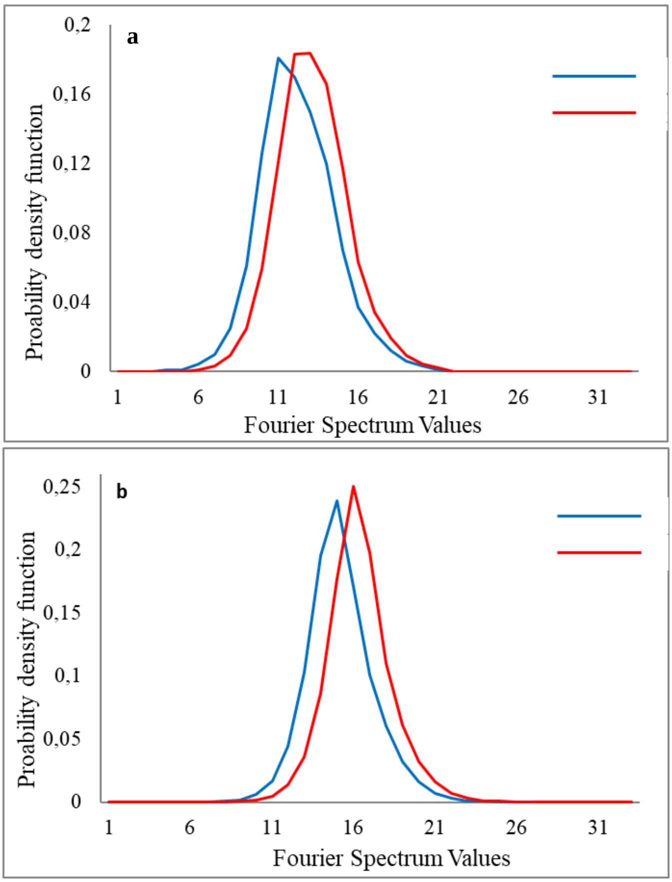
Increased heterogeneity or fragmentation in an area resulted in irregularities in the Fourier spectrum, where high values appeared in the outer part. The land cover of Gorgan comprised various land uses such as forests, rangelands, agriculture, urban areas, and water bodies. Given that most changes in this region were related to urban areas while other land uses experienced minimal changes over the 12 years, the Fourier spectra of this period (Fig. 6) bore a closer resemblance to each other compared to the Fourier analysis outputs at the urban land cover level (Fig. 5). The horizontal and vertical lines visible in the Fourier spectra indicated errors in the original images but did not significantly affect the interpretation of the results. A comparison between Fig. 6-a and 6-b revealed changes in the land cover of Gorgan between the years 1999 and 2010, with increased irregularity and heterogeneity observed in the 2010 Fourier spectrum. In the outer part of the spectrum for the year 1999, a uniform dark green color was predominant, whereas a mixture of light and dark green colors was observed in the outer part of the 2010 spectrum, indicating increased heterogeneity in that year.

Detecting this increase in irregularity and heterogeneity over the specified time relied on visual and descriptive interpretation of the Fourier analysis outputs. When the scattering radius of low frequencies in the Fourier spectrum extended towards the outer part, it signified increasing changes in the study area. Fourier analysis represented these changes as continuous displays of low, medium, and high frequencies, where low frequencies indicated homogeneity and high frequencies indicated heterogeneity and increased fragmentation. Therefore, any Fourier spectrum that showed higher frequencies implied the occurrence of habitat destruction processes such as fragmentation and habitat loss in the studied area.

Descriptive analysis of the Fourier outputs

To better visualize and accurately depict the details of fragmentation trends in the Fourier spectra, the density function of each output from Fourier analysis was plotted using R software. Fig. 7 illustrates the changes in Fourier spectrum values at the urban (Fig. 7-a) and landscape (Fig. 7-b) levels as a function of density and frequency histogram of values. In these plots, the left half represented low-frequency values, while the right half represented high-frequency values.

Fig. 7: Density function plots of the Fourier spectrum at the land cover level

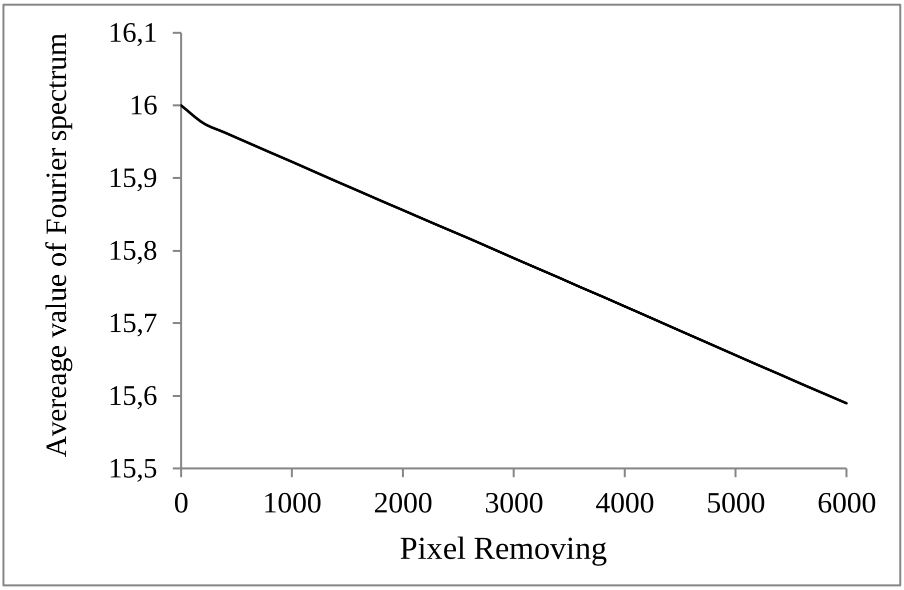


As discussed earlier, an increase in values in the Fourier spectrum indicated an increase in heterogeneity in the study area. According to Fig. 7, in the left half of the plot, the number of values in 1986 was higher than the corresponding values in 2010, indicating that the area was more homogeneous in 1986 compared to 2010. At the landscape level, a similar interpretation could be drawn from the urban-level results.

Sensitivity Analysis

Figure 8 presents the results of the sensitivity analysis of Fourier analysis. According to this figure, the initial mean of the Fourier spectrum was 16, which decreased to 15.9 in the first stage of random cell removal. Similarly, in each subsequent stage, the mean value gradually declined, reaching 15.5 in the final stage, where 6,000 cells were removed from the original image. Overall, these changes resulted in a slight reduction in the mean Fourier spectrum, reflecting the minor alterations in the land cover level of Gorgan County, which covers a vast area where 6,000 cells represent a relatively small portion. The sensitivity analysis results demonstrated that Fourier analysis could effectively capture subtle changes in land cover levels. However, it did so with small increments, highlighting the importance of considering this aspect when applying this tool.

Fig. 8: The results of sensitivity analysis of Fourier analysis



DISCUSSION

Fourier analysis has been previously utilized in remote sensing for tasks such as image calibration, systematic removal of noise from satellite images, determining appropriate scales in landscape studies, and integrating high-resolution data. In the present study, Fourier analysis was employed at both urban and landscape levels to detect landscape fragmentation dynamics. We found that (1) the Fourier analysis showed a slight decrease in the average spectrum, reflecting minor changes in land cover in Gorgan County. While it effectively captures subtle changes, it does so incrementally, emphasizing the need for caution when applying this too. (2) We observed increased fragmentation at both urban and landscape levels over 12 and 24-year periods through visual and descriptive analysis. This suggests that the approach is suitable for detecting changes in landscapes based on continuous images like PC1. (3) While Fourier analysis effectively identifies changes in landscape fragmentation, it cannot discern the specific types and quantities of altered land cover.

Therefore, while it offers valuable insights into the spatial distribution of changes, it does not offer detailed information about the nature or extent of these alterations. Integrating Fourier analysis with complementary methods or datasets that provide land cover classification could enhance the comprehensiveness of the analysis and provide a more detailed understanding of landscape dynamics. An alternative approach to overcoming this limitation is to focus specifically on selected land covers, such as forests, agricultural areas, or urban zones, rather than analyzing all covers simultaneously. By isolating certain land covers, it becomes easier to pinpoint which areas are most affected by fragmentation. For instance, by solely examining forest or urban areas, we can more accurately determine the extent of fragmentation within these specific categories, without interference from other land covers. This approach significantly improves the precision of detecting which cover types are contributing most to fragmentation, thus addressing the challenge of identifying the exact nature of landscape changes.

However, in agreement with the findings of Rocchini *et al.* (2013), we were able to detect the magnitude of changes in the area using Fourier analysis. Moreover, in detecting fragmented changes or habitat reduction, this analysis can effectively represent both small and large-scale changes in a landscape. This point was well observed in this study as two landscapes with different areas and amounts of variation were considered as input for Fourier analysis, and the diagrams showed the changes in landscape compared to urban landscapes. However, it should be noted that the time intervals between these landscapes were also influential because the changes will be greater over time. Therefore, in the application of Fourier analysis in landscape fragmentation studies, this point should be considered that the wider the study area and the longer the time intervals between images, the better results this approach provides.

Sensitivity analysis of Fourier analysis also had important objectives, which no study had previously focused on. This important objective was addressed in this study, demonstrating new aspects of this tool. The results of sensitivity analysis showed that Fourier analysis can detect changes, but it represents these changes with small numbers, such that this tool showed a change of 200 cells in a wide area such as the landscape of Gorgan County. In general, the results of this study showed an increase in spatial heterogeneity over 12 and 24-year periods in both landscape and urban areas. Considering that various factors such as scale, spatial resolution, and thematic relevance affect the accuracy of satellite image classification, this research directly utilized satellite images to investigate landform changes in Gorgan County, thus avoiding errors arising from human performance. The results of this study also demonstrated that continuous temporal approaches require less time and cost compared to discrete approaches and can effectively represent and measure landform changes.

CONCLUSION

In conclusion, this study aimed to achieve several key objectives. First, we sought to assess the effectiveness of Fourier analysis in quantifying heterogeneous changes in the landscape and urban patterns of Gorgan County, over the past 24 years. Our findings indicated a slight decrease in the average spectrum, suggesting minimal changes in land cover during this period. Second, we evaluated the strengths and limitations of the Fourier analysis method for capturing landscape and urban transformations. Our observations revealed an increase in fragmentation at both urban and landscape levels over 12- and 24-year intervals, as evidenced by visual and descriptive analyses. Lastly, we performed a sensitivity analysis to gauge the method's responsiveness to minor alterations in landscape and urban patterns. The results highlighted that while Fourier analysis can effectively detect subtle changes in land cover, it does so with small increments, underscoring the need to consider this characteristic when applying the method.

Integrating Fourier analysis with machine learning and GIS approaches can enhance its ability to detect and map landscape changes more precisely. While Fourier analysis captures the magnitude of change, machine learning algorithms like Random Forest or deep learning can classify land cover types, providing detailed insights into which areas (e.g., forests, agriculture) are being affected. GIS tools can spatially localize these changes, allowing researchers to map and track fragmentation across landscapes. Combining these methods would enable a more robust analysis, improving both spatial accuracy and thematic detail, and addressing the limitations of Fourier analysis when used alone.

Landsat data, while highly valuable for long-term ecological monitoring, does come with certain limitations, particularly regarding its spatial resolution. With a 30-meter resolution, Landsat imagery provides a moderate level of detail, which is sufficient for broad-scale landscape analyses but may miss finer-scale fragmentation patterns. This resolution limitation could impact the study’s ability to detect small patches of fragmented landscapes, especially in areas with heterogeneous land cover. Consequently, some smaller-scale fragmentation might go undetected, potentially leading to an underestimation of the overall fragmentation levels and affecting the study's conclusions. To better address how these limitations might affect the results, it is important to recognize that lower spatial resolution may blur the boundaries between different land cover types, leading to less accurate detection of fragmentation at smaller scales. For example, small forest patches or narrow corridors, which are critical for ecological connectivity, may not be fully captured in Landsat imagery. This could result in a more generalized view of fragmentation, missing the finer nuances of landscape changes.

In future studies, integrating higher-resolution imagery could significantly enhance the ability to detect and analyze fragmentation. Satellite systems like Sentinel-2, which offer a 10-meter spatial resolution, or commercial satellites that provide even higher resolution, could be valuable additions. These higher-resolution data sources would allow for more precise mapping of small-scale landscape changes, providing a clearer picture of how fragmentation is occurring across different land cover types. By combining these data with Landsat’s historical depth, future research could balance broad-scale monitoring with finer-scale detection, leading to a more comprehensive understanding of landscape fragmentation processes.

CONFLICT OF INTEREST

The authors declare that they have no competing interests.

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