Research on environmental changes based on fractal characteristics of satellite images

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Abstract

Most natural structures that are widely studied today using computer science have a complex fractal structure. Fractal analysis of such structures is used to model, study, and explain the properties of surfaces and structures of complex objects in various fields of science and technology. Images of a large number of natural surfaces and structures are satellite images that exhibit fractal properties. Satellite images in modern life have high spatial resolution, which gives researchers and users satisfactory initial data for solving various types of problems. A promising direction for increasing the informativeness of satellite images is the use of fractal image analysis methods. The complexity of the forms of the underlying surface and vegetation can be described using the fractal dimension. Characteristic values of the fractal dimension allow decoding of space images.

The paper proposes a method for studying environmental changes in satellite images based on the calculation of fractal characteristics, such as fractal dimension, fractal distribution and fractal segmentation. The ecological indicators for assessing the state of the environment were selected as trends in forest numbers, water and land resources. Satellite images of the Amazon forests, Bolivia in 1991, 1996, 2006, 2012, 2016, 2020, which were subjected to mass deforestation, were selected for the study. The experimental results show that the fractal dimension increases each time (Fractal Dimension (FR) = 1.441 in 1991, FR = 1.825 in 2020), and the green areas in this area decrease. The depth of the seas (Black Sea, Tyrrhenian Sea, Mediterranean Sea, Philippine Sea) was studied. The least homogeneous with the largest amplitude of distribution modes has the fractal distribution of the Philippine Sea, which indicates a more pronounced relief of the seabed. As a result of the study of winter fields with different levels of snow cover, it was found that an increase in its value leads to an increase in the value of the fractal dimension (FR=1.702 February, FR=1.894 March). Thus, fractal analysis of winter fields allows us to estimate the relative amount of moisture that will enter the soil in the spring.

The study highlights the need for further research in developing more efficient fractal methods to improve the accuracy of change area detection, which will favor the analysis of the causes and consequences of the environmental situation.

Keywords

fractal, dimension, distribution, segmentation, analysis, satellite image, environment.

1. Introduction

Today, fractal analysis methods are actively used in various fields of knowledge to study objects and structures that have fractal properties. A fractal is an irregular, self-similar structure, small parts of which, when arbitrarily enlarged, are similar to itself [1]. That is why fractals and fractal methods allow us to describe and study natural objects that are difficult to describe using traditional geometric methods [3, 4]. And that is why fractal analysis methods are actively used in medicine, computer graphics, in morphology when studying the shape and structure of natural objects, in the study of metallic materials, etc.

MoDaST 2025: Modern Data Science Technologies Doctoral Consortium, June, 15, 2025, Lviv, Ukraine

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Self-similarity is the main characteristic of a fractal and represents a uniform organization over a wide range of scales. Fractals can be used to describe the shapes of natural objects, their boundaries with all their roughness [10, 11]. In nature, objects have clear intervals where they manifest their fractal nature.

The main fractal characteristic is the fractal dimension [14, 15]. Fractal dimension is a quantitative characteristic that describes the complexity and self-similarity of fractal objects and can take values in the range from 1 to 2 for binary images and from 2 to 3 for halftone images. Fractal dimension shows how the detail of a fractal object changes when the scale changes [2].

In addition, the fractal dimension of each fragment of the image has different values and will differ from the dimension of the entire image as a whole. Therefore, a distinction is made between global and local fractal dimensions. Global fractal dimension refers to the dimension of the entire image, and local fractal dimensions refer to the dimensions of different fragments of the image. Thus, the global fractal dimension describes the overall complexity of a fractal object, taking into account its structure at different scales. At the same time, local fractal dimension characterizes the complexity at a certain point or at a certain scale and can change at different points of the fractal object. Local dimension is relevant for analyzing changes in the structure of a fractal object in its different parts. Therefore, the study of the distribution of local fractal dimensions, which is proposed in the work, is appropriate and relevant.

2. Related Work

Recently, fractal analysis methods have been actively developed and continue to develop as a powerful tool for studying complex objects and structures in various fields of knowledge. Fractal analysis consists of identifying and studying fractal structures in a specific problem, and then using this knowledge to understand patterns, predict behavior, and find solutions. That is why it is actively used in solving various problems: for plant recognition [4], for water detection in satellite images [9], for pollution detection [10, 11], etc.

Researches [8, 12, 13, 18-20] are devoted to the problems of classifying structures and objects according to fractal characteristics.

In [13] classification of multispectral remotely sensed data is investigated with a special focus on uncertainty analysis in the produced land-cover maps.

In paper [12], a TM multi-spectral satellite image is adopted for the purpose of supervised classification. The traditional method of segmentation, namely the Quad tree, is applied as a pre-processing step. For each segmented block, the fractal features (fractal dimension and lacunarity) are determined to be used as a maximum likelihood classifier. The results showed that the fractal dimension was not able to classify the segmented blocks, while the lacunarity gave good classification results. In general, the fractal geometry was found to be an efficient parameter for describing the image. The results show that the overall classification accuracy is 85.5%. In [17], supervised classification was carried out using fractal dimensionality, which is used to classify the target part of the image. Five different classes were identified and the classification accuracy was 97%, indicating that the adopted fractal feature is able to recognize the different classes found in the image with high accuracy.

Today, image segmentation methods are actively studied and used to solve problems of determining environmental changes [5, 6, 7]. Fractal segmentation differs from the usual one, since it involves the process of dividing an image into parts that have the properties of fractals, that is, self-similar at different scales. That is why fractal segmentation allows you to highlight complex structures and patterns that may be invisible when using traditional segmentation methods. Fractal segmentation is used in many areas, such as medical imaging, satellite image processing, image analysis in scientific research, as well as in computer graphics to create realistic images.

Having analyzed the works devoted to fractal analysis methods, we can conclude that further research is needed to adapt existing and create new methods for detecting environmental changes based on the fractal characteristics of satellite images.

3. Research Objectives

The aim of the work is to develop a method that allows analyzing satellite images of the relevant territory at different time intervals and tracking changes in the environment. The study calculated the fractal characteristics of satellite images, such as fractal dimension, constructing the distribution of local fractal dimensions (fractal distribution), and processing images using the fractal segmentation method. The work includes studying the fractal characteristics of: 1) satellite images of Amazonian forests (1991, 1996, 2006, 2012, 2016, 2020); 2) satellite images of seas with different maximum depths (Black Sea, Tyrrhenian Sea, Mediterranean Sea, Philippine Sea); 3) satellite images of winter fields (January, February, March).

4. Methodology

In this work, the fractal dimension will be understood as the Hausdorff-Bezikovitch dimension. Fractal dimension was calculated using the BOX COUNTING method [16], which can be applied to various objects that do not have exact self-similarity.

During the calculations, all images were converted to binary. Therefore, an important step in fractal analysis is binarization, which is a thresholding operation and the result of which is a binary image. The purpose of binarization is to radically reduce the amount of information contained in the image.

When binarizing an image, it must be determined whether a useful signal or background is observed in an image pixel using a threshold separation operation, which consists of comparing the brightness value of each image pixel with a given threshold value. For image processing, the average value method was used in the work, which uses the average value of all image pixels as a threshold.

Figure 1 shows the result of testing the work of the developed software module for determining the fractal dimension of classical fractals, the Sierpinski triangle and the Koch curve, the dimensions of which are known in advance - 1.585 and 1.2618, respectively. The results of the software module coincide with the theoretical values of the fractal dimension.

The strong dependence of the fractal dimension on the image fragment prevents an objective assessment of the dimension. But this fact indicates the possibility of anisotropy of this surface. Therefore, determining the global fractal dimension of the image is insufficient for the analysis of fractal objects and their properties. To solve this problem, the image was divided into small fragments, and local fractal dimensions were estimated in these fragments. After that, their empirical distribution (fractal distribution) was constructed, which gives an idea of the features of the objects in the image.

To construct the fractal distribution, the sliding window method is proposed in the work, which consists of determining the fractal dimension within the window, the size of which can be set arbitrarily. The window is moved pixel by pixel across the image. At the same time, the fractal dimension of the image that falls into the sliding window is calculated at each step. After obtaining the local fractal dimensions, their empirical probability distribution W(D) / Wmax(D) is constructed.

Fractal image segmentation is the process of dividing a digital image into segments that have the same or similar values of fractal dimension. Thus, fractal segmentation allows you to select objects in the image that have the same fractal properties. The developed software module allows you to perform image segmentation by grouping segments with similar fractal dimension by displaying them in color.

The following algorithm was proposed and implemented for fractal image segmentation:

1. The local fractal dimensions of the image are calculated with a sliding window size from 5 to 21 pixels.
2. Image fragments that have the same local fractal dimensions are assigned the same color.

The color segmentation algorithm uses the RGB color spectrum, starting from red (255, 0, 0), which corresponds to a fractal dimension of 0, and ending with blue (0, 0, 255), which in turn corresponds to a dimension of 2.

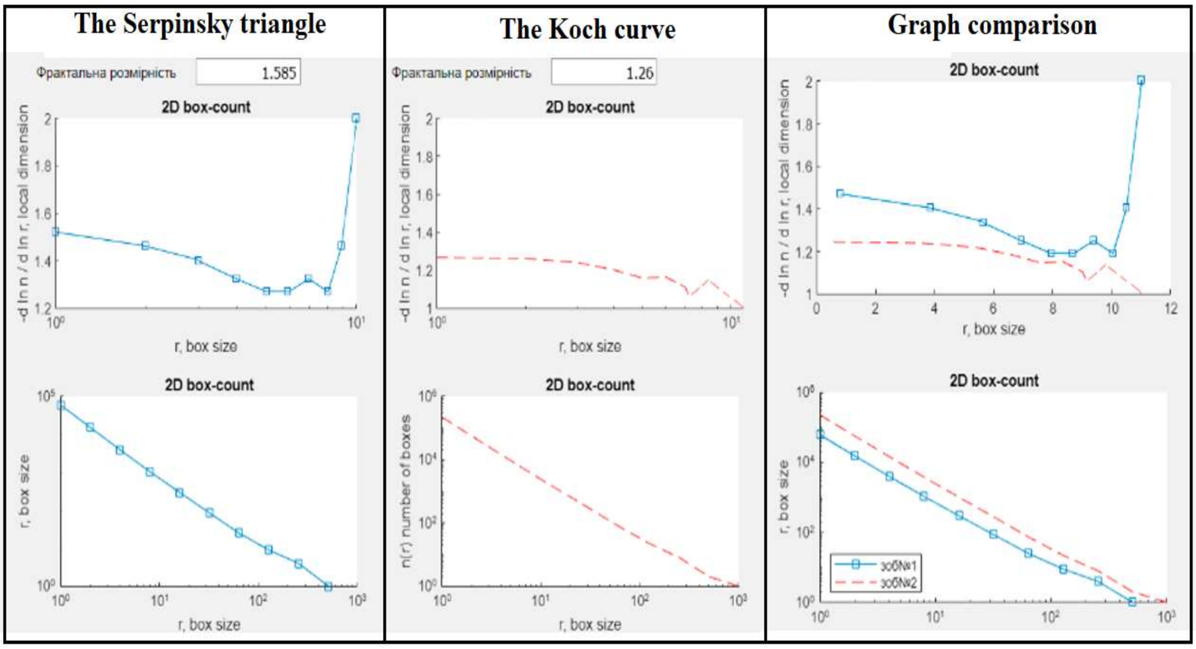

Figure 1: Example of software module operation.

5. Experiments and results

The work analyzed the fractal characteristics of the following series of satellite images:

1) satellite images of the Amazon forests (1991, 1996, 2006, 2012, 2016, 2020);

2) satellite images of seas with different maximum depths (Black Sea, Tyrrhenian Sea, Mediterranean Sea, Philippine Sea);

3) satellite images of winter fields (January, February, March).

To ensure the accuracy of each series of experiments, satellite images of the same PNG format and dimensions were selected.

Study of fractal characteristics of satellite images of Amazonian forests

Satellite images of Amazonian forests in 1991, 1996, 2006, 2012, 2016, 2020, which were subjected to mass deforestation, were selected for the study (Figure 2). The results of each experiment show that the fractal dimension increases each time, and the green areas in a given area decrease. Figure 2 shows a graph of changes in the fractal dimension values of Amazonian forests in the interval 1991-2020. Thus, it is possible to demonstrate the increase in deforestation based on fractal dimension data.

Figure 3 shows the results of fractal image segmentation, which show that when deforestation occurs in the Amazon, there is a tendency to increase the light parts and increase the fractal dimension of the images.

Figure 4 shows fractal distributions of satellite images of the Amazonian forests during the period 1991-2020. The fractal distributions of 1991-1996, 2006-2012, and 2016-2020 have slight differences in density, but the number of distribution modes is the same, and the fractal dimensions differ by an average of 5%. The fractal distributions have significant differences in the number and nature of distribution modes in 1996-2006 and 2012-2016, and the fractal dimension increased by more than 10%. This may indicate more intensive deforestation during this period. Thus, fractal analysis can be used to track illegal deforestation.

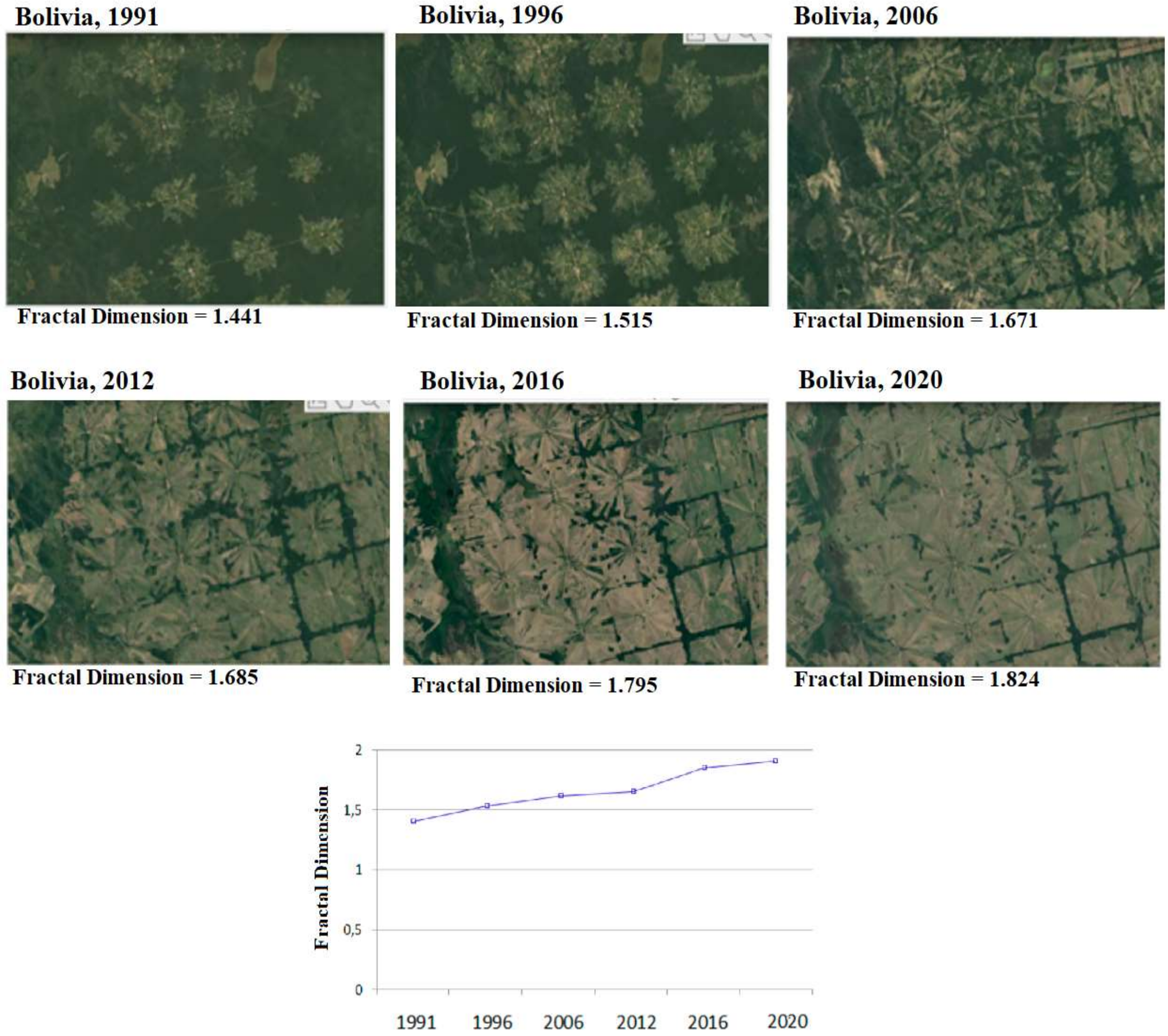

Figure 2: Results of the fractal dimension of Amazonian forests in 1991-2020 years

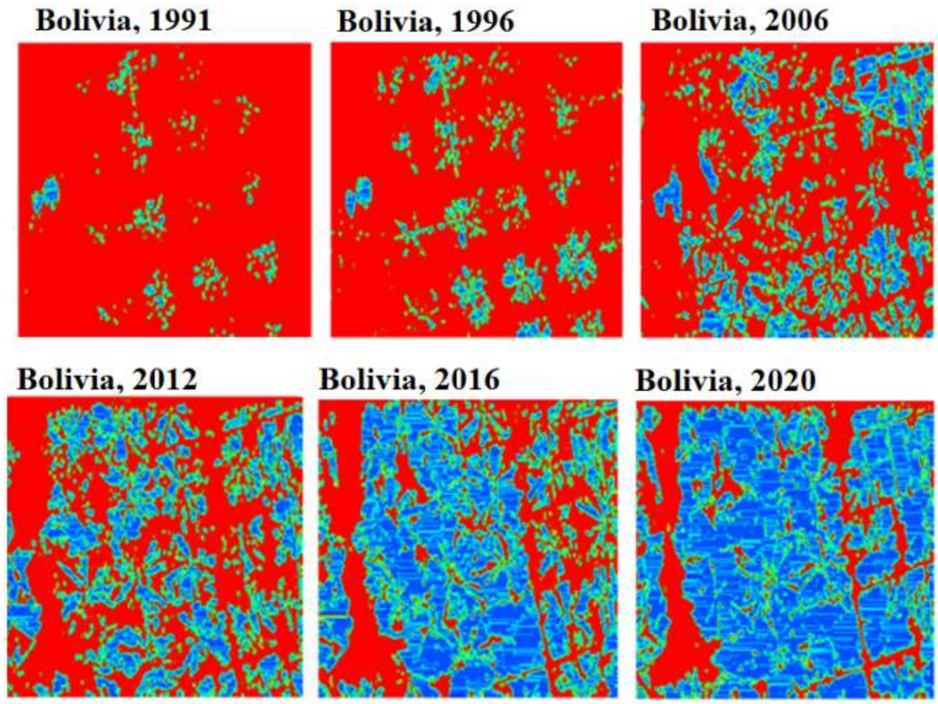

Figure 3: Fractal segmentation of Amazon forest images from 1991-2020.

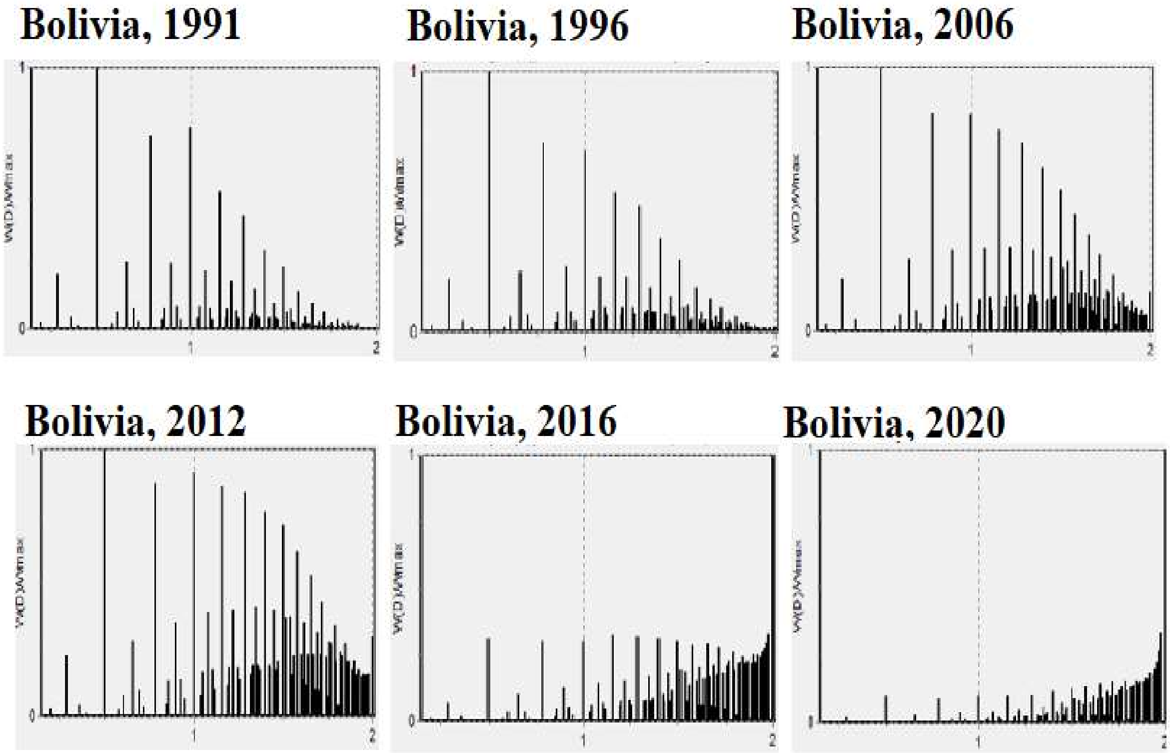

Figure 4: Fractal distributions of Amazon forest images from 1991-2020 years.

Study of fractal characteristics of satellite images of seas with different maximum depths

Satellite images of seas with different maximum depths were selected for the study: the Black Sea (depth 2212m), the Tyrrhenian Sea (depth 3785m), the Mediterranean Sea (depth 5267m), and the Philippine Sea (depth 10540m).

After analyzing the obtained data, it was determined that the fractal dimension decreases with increasing maximum sea depth.

Figure 5 shows the results of fractal segmentation of satellite images and their fractal distribution. Satellite images of the Black, Tyrrhenian and Mediterranean Seas have fractal distributions similar in intensity and number of modes. The least homogeneous with the largest amplitude of mode distribution is the fractal distribution of the Philippine Sea. This nature of the fractal distribution indicates a more pronounced relief of the seabed.

The largest fractal dimension of 1.854 corresponds to the satellite image of the Black Sea, which has the smallest depth in the given sample.

Thus, using fractal analysis, it is possible to determine the relative depth of a body of water from satellite images. In addition, using local fractal dimensions and fractal segmentation, it is possible to track the deepest and shallowest areas of a body of water. This information can be used in the control of surface and underwater vessels.

Study of fractal characteristics of satellite images of winter fields

Satellite images of winter fields with different amounts of snow cover were selected for the study on January 8, 2022, February 12, 2022, and March 22, 2022. As a result of fractal analysis of satellite images of the territories, the influence of snow cover on fractal characteristics was investigated (Figure 6).

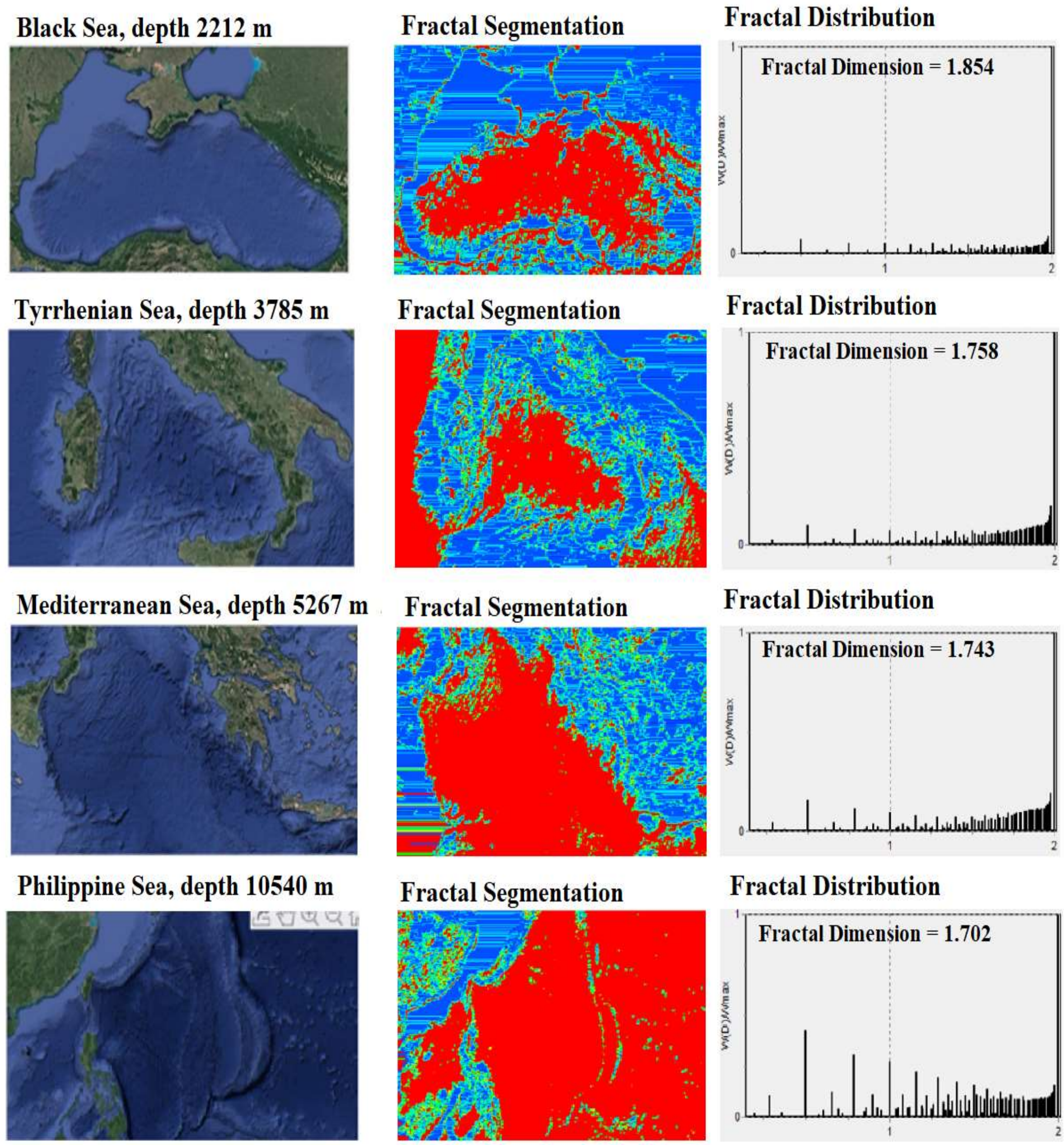

Figure 5: Fractal analysis of satellite images of seas with different maximum depths.

As a result of the study, it was found that an increase in the amount of snow cover leads to an increase in the amount of fractal dimension. The images for January and February have almost the same level of snow cover; therefore, the fractal dimensions of these images are almost the same: 1.702 and 1.714. The image for March has a significantly larger snow cover, to which the value of the fractal dimension immediately reacts with a jump up - 1.894. A similar result is reflected in the fractal distributions: the fractal distributions of the field images for January and February almost do not differ in the number and amplitude of the distribution modes. But the image for March has a completely different distribution pattern.

Fractal segmentation allows you to immediately determine the relative amount of snow cover, which is displayed in cyan. The largest areas of snow cover are observed in the fractal segmentation image for March.

Thus, fractal analysis of winter fields allows us to estimate the relative amount of moisture that will enter the soil in the spring.

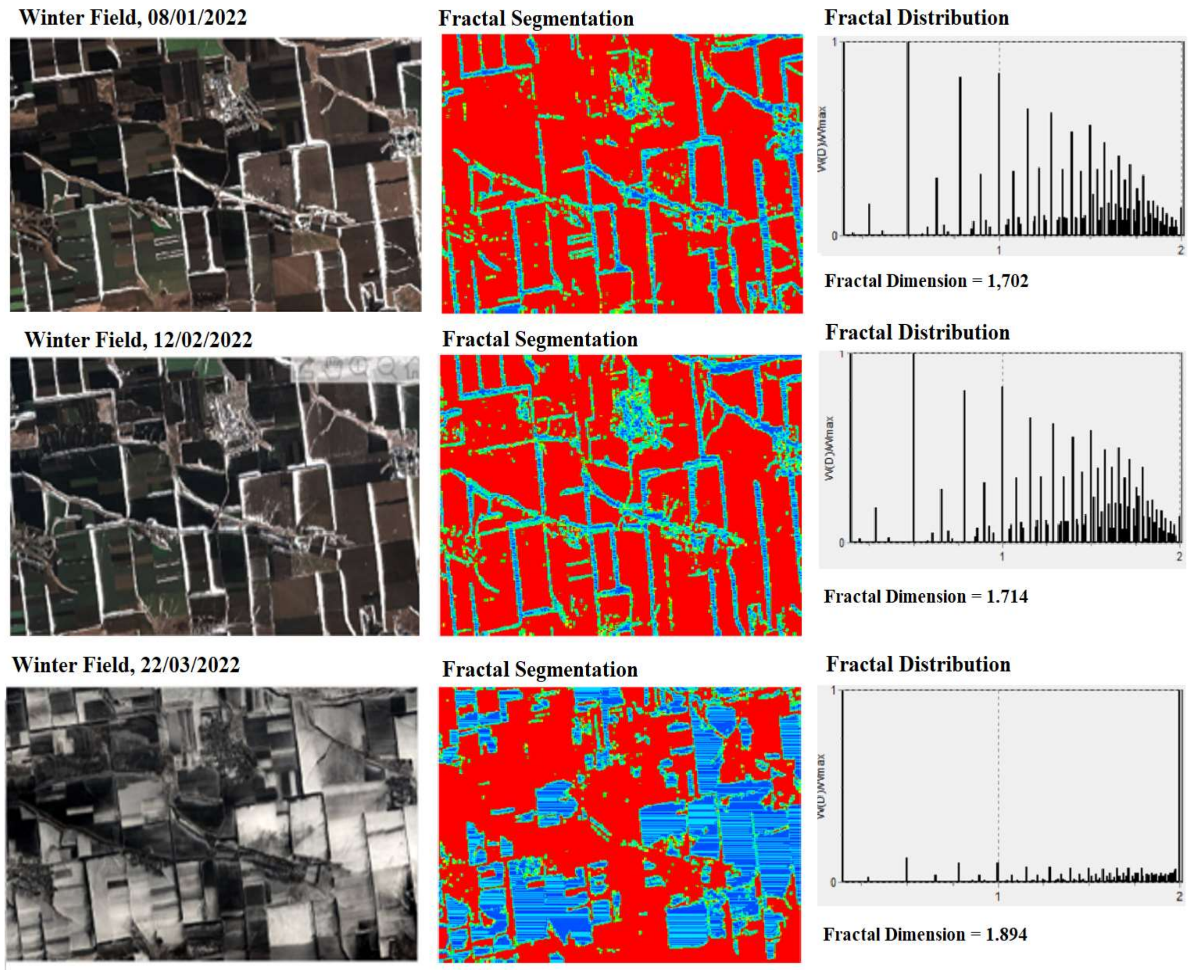

Figure 6: Fractal analysis of satellite images of winter fields with different amounts of snow cover.

6. Conclusions

The paper proposes a method that allows analyzing satellite images of the corresponding territory at different time intervals. Using the proposed method, fractal characteristics of satellite images were calculated, such as fractal dimension, construction of the distribution of local fractal dimensions (fractal distribution), and image processing was performed using the fractal segmentation method, which allowed tracking changes in the environment.

As a result of the research, the following results were obtained:

1) When studying satellite images of the Amazonian forests (1991, 1996, 2006, 2012, 2016, 2020), it was determined that when the Amazonian forests are cut down, there is a tendency to increase the light parts of the fractal segmentation and increase the fractal dimension of the images. At the same time, the fractal distributions of 1991-1996, 2006-2012 and 2016-2020 have slight differences in density, but the number of distribution modes is the same, and the fractal dimensions differ by an average of 5%. The fractal distributions of 1996-2006 and 2012-2016 have significant differences in the number and nature of distribution modes, and the fractal dimension increased by more than 10%. This may indicate more intensive deforestation during this period. Thus, fractal analysis can be used to track illegal deforestation.

2) When studying satellite images of seas with different maximum depths (Black Sea, Tyrrhenian Sea, Mediterranean Sea, Philippine Sea), it was determined that the fractal dimension decreases with increasing maximum sea depth. Satellite images of the Black, Tyrrhenian and Mediterranean Seas have fractal distributions similar in intensity and number of modes. The least homogeneous with the largest amplitude of modes distribution is the fractal distribution of the Philippine Sea. This nature of the fractal distribution indicates a more pronounced relief of the seabed. The largest fractal

dimension of 1.854 corresponds to the satellite image of the Black Sea, which has the smallest depth in the given sample. Thus, using fractal analysis, it is possible to determine the relative depth of a body of water from satellite images. In addition, using local fractal dimensions and fractal segmentation, it is possible to track the deepest areas of a reservoir and the areas with the smallest depth.

3) When studying satellite images of winter fields (January, February, March), it was found that an increase in the amount of snow cover leads to an increase in the amount of fractal dimension. Images for January and February have almost the same level of snow cover, therefore the fractal dimensions of these images are almost the same: 1.702 and 1.714. The image for March has a significantly larger snow cover, to which the value of the fractal dimension immediately reacts with a jump up - 1.894. Thus, fractal analysis of winter fields allows you to estimate the relative amount of moisture that will enter the soil in the spring.

Declaration on Generative AI

The authors have not employed any Generative AI tools.

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