RESEARCH PAPER

MONITORING OF FRAGILE ECOSYSTEMS WITH SPECTRAL INDICES USING SENTINEL-2A MSI DATA IN SHAHDAGH NATIONAL PARK

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ABSTRACT. Studying ecosystems using remote sensing technologies is very relevant since it checks the accuracy of the results of modern research. This study aims to monitor environmental changes in ecosystems of the Shahdagh National Park and its surrounding areas in Azerbaijan using Sentinel 2A MSI data. The study aimed to examine and monitor changes in vegetation, water resources, and drought conditions of the study area in recent years. For analyzing and observing these ecosystems Normalized Difference Vegetation Index (NDVI), Normalized Difference Water Index (NDWI), and Normalized Difference Drought Index (NDDI) were calculated using multi-band methods. Obtained indices were compared and changes were investigated analyzing satellite-derived methods. For proper monitoring and assessment of relevant ecosystems, there had been determined 3,825 fishnet points for the study area. This made it possible to compare and coordinate the results of the indices more accurately. After linking fishnet points to raster indices, classification had been made for measuring ecosystems indicators. Vegetation assessments revealed a partial expansion of sparse vegetation or bare rocks, river valleys, as well as nival, subnival, and partial subalpine meadows from 15.1% to 18.1%. Another growth indicator is a significant increase of dense forest ecosystems from 2.3% to 9.2%. According to the results decreases are observed in sparse forests, arable lands, pastures, and shrubs, which are more sensitive to anthropogenic factors. Monitoring of the indices shows that low-humidity areas increase as droughts intensify, especially in plain areas. Finally, the study revealed that the introduction of a specially protected regime within the national park makes ecosystems more sustainable.

KEYWORDS: environmental monitoring, NDVI, NDWI, NDDI, Shahdagh National Park, ecosystem

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INTRODUCTION

The recent acceleration of economic and social development has led to the wider use of the concept of sustainable development. The term, first mentioned in the Brundtland Report (1987), is defined as "… the needs of the present without compromising the ability of future generations to meet their own needs". The subsequent Rio Declaration (UNCED 1992) on sustainable development states that the only way to achieve long-term economic progress is to link it to environmental protection. At the 2005 World Summit of the United Nations, the concept was explained in more detail with three key directions: economic development, social development, and environmental protection.

Today, environmental protection has become a very important part of the sustainable development approach, as well as our daily activities as a common commitment. In terms of ensuring sustainable development the identification of fragile ecosystems is an essential part of the management of nature conservation. Although some researchers attribute this approach to natural factors, others explain it by the human's impact on nature (Nilsson 1995). The increasing impact of human activities on ecosystems in recent years has provided a basis for assessing such areas.

Recent studies show that remote sensing (RS) technologies provide data support for environmental assessments, which has become an important evaluation tool along with Geographic Information Systems (GIS) (Hou et al., 2016; Zhao et al., 2018; Belgiu & Csillik 2018; Phinzi & Ngetar 2019). These methods are widely used to monitor environmental issues. For example, Vihervaara et al. (2017) analyzed how national biodiversity monitoring could be developed by using RS. Griffiths et al. (2014) used Landsat data with five-year intervals to investigate changes in forest types, forest disturbances, and forest recovery. Rawat & Kumar (2015) tried to illustrate dynamics of land use/cover by using multi-temporal satellite imagery. Chu & Guo (2014) attempted to provide RS data tools for preventing and monitoring forest fires and understanding how the environment responds to them. Zhao & Lu (2018) analyzed data and methods of landslide processes using remote sensing techniques used in many different studies. Shahabi et al. (2020) identified flood-prone areas using Sentinel sensors in their studies and propose flood sensitivity mapping techniques.

In this research, the datasets used in the analysis are Sentinel 2A MSI (Toming et al. 2016; Sakowska et al. 2016; Sonobe et al. 2018; Othman et al. 2014) for evaluating remote sensing indices. Recent studies in this area are showing positive results in the research of environment and ecosystem issues (Filipponi et al. 2018; Giuliani et al. 2019; Wang et al. 2019).

This study aims to monitor environmental changes and to determine the fragile ecosystems using spectral indices calculated from Sentinel 2A MSI data. For this purpose, Normalized Difference Vegetation Index (NDVI), Normalized Difference Water Index (NDWI), and Normalized Difference Drought Index (NDDI) were determined for the study area, using Green, Red, and NIR bands with 10 m resolution from relevant multispectral images. The multi-band method is based on reflective variations of the bands and extracts index-based values for analysis of appropriate natural resources (Qiao C. et al. 2012). In recent years these indices have been used very widely in ecosystem monitoring (Li Y. et al. 2017; Ali et al. 2019; Higginbottom 2020; Semeraro et al. 2020).

The main objectives of the study are to apply and examine the NDVI, NDWI, and NDDI in addition to providing a basis for monitoring changes in vegetation, water resources, and drought conditions of the Shahdagh National Park and its surroundings over the past three years using Sentinel 2A multispectral satellite imagery. This procedure ensures that the environment is examined in a combined and transparent manner, considering the needs for the progress of the area; informs stakeholders about the impacts of the area on the environmental planning activities or processes. Assessing the indices can help identify areas of strategic significance for nature conservation, including environmental networks.

Ecological conditions are mainly associated with an effective assessment of ecosystems (Yang and Chen 2015). Consequently, the evaluation of ecosystems is very significant for achieving sustainable development in the regional case and environmental security for the national park and surroundings. Within modern technologies, satellite-based assessments and comparisons of ecosystems can save time and money as well. More importantly, there has been no regional studies of the ecosystems of Shahdagh National Park using remote sensing technologies. Therefore, conducting research in the study area is not only an attempt to study the ecosystems of the South Caucasus in general, but also the basis for future research.

MATERIALS AND METHODS

Study Area

The study was conducted in the Shahdagh National Park, the largest national park in the South Caucasus. The National Park covers the middle and high mountains of the Greater Caucasus within Azerbaijan. The current area of the National Park is 130,508.1 hectares. The National Park covers the mountainous parts of six administrative districts of Azerbaijan: Oghuz, Gabala, Ismayilli, Shamakhi, Guba, and Gusar (Jabrayilov 2021).

The territory of the National Park includes the mountain landscapes unique in the region, begins approximately at an altitude of 1000 m above sea level and continues to the highest peaks (Bazarduzu mt, 4466 m; Shahdagh mt, 4243 m; Tufandagh mt, 4191 m, etc.) of the country. Hypsometric indicators and location of the study area is shown in Figure 1. The elevation difference above sea level is based on a Digital Elevation Model (JAXA/METI 2007). The main types of landscapes in the national park and surrounding areas are forest, forest-steppe, and shrub landscapes of low and medium mountains, subalpine and alpine meadows, subnival and nival landscapes of high mountains. The study area is divided into four climate types according to climatic characteristics: 1. Cold climate type with dry winters on the north-eastern slopes of the Main Caucasus Range at an altitude of 1,400–2,700 m above sea level. 2. Mild-warm climate with equal distribution of precipitation among all seasons on the southern and north-eastern slopes of the Greater Caucasus. 3. Cold climate with abundant rainfall in all seasons in the southern zone of the Main Caucasus Range, high mountain-forest, and alpine zone. 4. Mountain tundra climate in high mountain areas with an absolute height of more than 2,700 m.

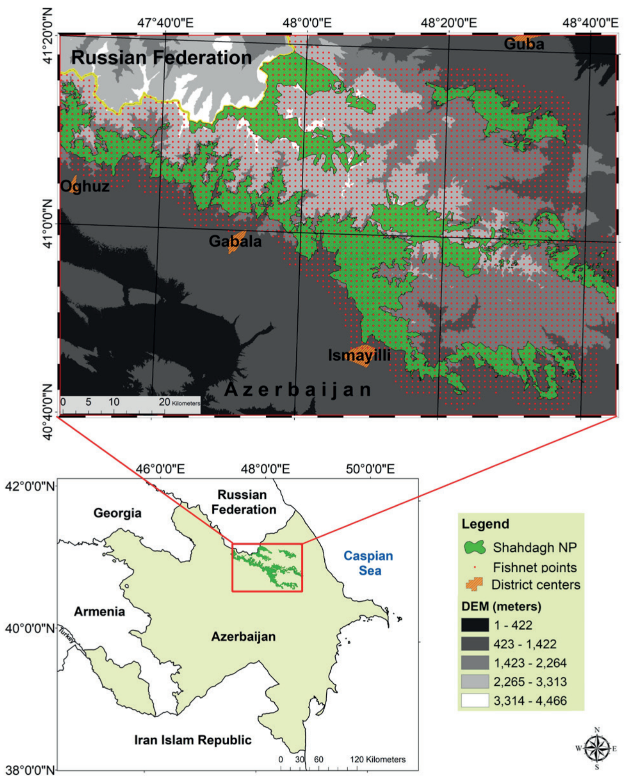

Fig. 1. Shahdagh National Park and fishnet of study area

Data and methodology

Sentinel 2A satellite imagery provided by the European Space Agency (ESA) was used in the study. The data were downloaded from USGS Global Visualization Viewer. The acquisition date of the images is July 28, 2017 and June 2, 2020. It was impossible to select the same months for the study. This is because the satellite images for the 6th, 8th, and 9th months of 2017 were not selected due to high cloudiness. Images for the 7th and 8th months of 2020 were also not considered appropriate due to high cloud cover (sometimes up to 70%). Thus, the images were selected because of the minimum value of the cloud cover. The cloud cover of the images is 0.203% and 0.278%, respectively. From the multispectral data for the study, the 3rd, 4th, and 8th bands were processed with a spatial resolution of 10 m for each using Coordinate System WGS 1984, UTM Zone 39N (Table 1). ArcGIS 10.8 and ERDAS İmagine softwarewere used for data analysis, processing, and mapping.

It is known that by using multispectral images, it is possible to increase the brightness value of the target objects and reduce the brightness of other objects by calculating the difference between the reflection values of multiple bands (Jiang et al. 2021). To observe and assess fragile ecosystems there were calculated Normalized Difference Vegetation Index (NDVI) (Carlson and Ripley 1997; Pettorelli et al. 2005; Yuan et al. 2019), Normalized Difference Water Index (NDWI) (McFeeters 1996, Zhang et al. 2008; Yang 2017), and Normalized Difference Drought Index (NDDI) (Dobri et al. 2021; Gu et al. 2007; Lange et al. 2017) (Fig. 2). According to the existing methodology (Renza 2010), the NDVI and NDWI values were converted to eight bits (0–255) so that the values obtained from the NDDI calculation varied between -1 and +1. To compare the values obtained from indices, a fishnet was set up for the study area. The number of points for fishnet is 3,825. The distance between the points is 1,000 m (figure 1).

RESULTS AND DISCUSSION

Using Sentinel 2 imagery in the study has made the determination of potential fragile ecosystems more effective for real time. The integration of Geographic Information Systems (GIS) and remote sensing technologies have considerably facilitated the observation of such areas. These assessments can be used as a basis of land use standards at more detailed planning levels or on environmental optimization. These satellite images allowed for attempts to identify changes in ecosystems in the Shahdag National Park and surrounding areas in recent years. The fishnet assigned to the area is linked to compare the calculated values of the corresponding indices. The indices obtained on the basis of satellite data for 2017 and 2020 were divided into categories and the number of points belonging to each category was determined. Because the area is mountainous, our analysis was conducted for the summer months.

Figure 3 shows colored NDVI values calculated from Sentinel 2 images for 2017 and 2020. For the fishnet area, NDVI values range from 0.84 to -0.14 for 2017 and from 0.85 to -0.16 for 2020. Average values were almost the same for both years – 0.50 and 0.51 respectively. The standard deviation for 2017 was 0.24; for 2020 it was 0.26. The NDVI values were categorized to compare the number of overlapping fishnet points for each year (Table 2). As can be seen from the table the number of points increased up to 0.2 index values for the relevant years. Landscapes with sparse vegetation or bare rocky river valleys are more compatible for such areas. High mountainous areas are very typical for these points. Thus, this indicator shows a slight expansion of the nival, subnival, and partially subalpine meadow zones according to the satellite images. The number of values between 0.2 and 0.8 decreased. Such areas may include sparse or medium-density forests, arable lands, pastures, and shrubs as well. In particular, given that these landscapes are more sensitive to anthropogenic factors, the reduction leads to increased fragility of these

Table 1. Sentinel 2A satellite data bands used in the study

Spectral bands	Central wavelength, μm	Wavelength, μm (min - max)	Bandwidth	Resolution, m
Band 3 – Green	0.560	0.5425–0.5775	0.045	10
Band 4 – Red	0.665	0.646 – 0.685	0.039	10
Band 8 – NIR	0.842	0.7845–0.8995	0.141	10

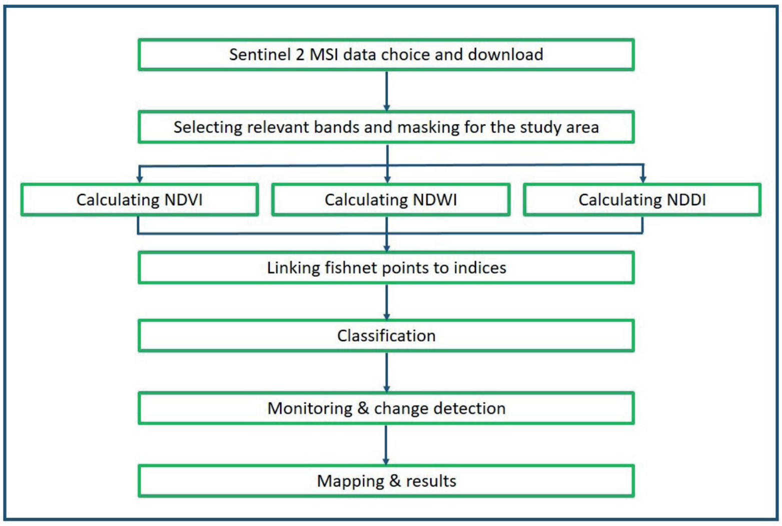

Fig. 2. Flowchart of the study

natural resources in these zones. It should be noted that such areas are most common in the surrounding areas of the national park. These sensitive landscapes are transformed due to the intensification of human activity in recent years in the settlements located in the surroundings of the national park and the consequent increase of anthropogenic impacts. In the alpine meadow zone, this transformation is due to unsystematic grazing (Ismayilov and Jabrayilov 2019). Grazing pressure, especially in the summer months, leads to degradation and deterioration of vegetation and soil cover. These landscapes should be considered more fragile ecosystems.

And finally, there was a significant increase in the number of points above the index value of 0.8 (from 86 to 350). These points are suitable for densely forested areas. Dense forest landscapes are more pronounced within the territory of the national park.

Water is one of the most valuable and important natural resources of the region. For this purpose, spectral signature feature analysis for the study area was performed. Another calculated index is NDWI, which is shown in Figure 4. This multi-band method uses the reflective varieties of each band and extracts relevant resources for the analysis. The values of these indices are adjusted to the fishnet points. The maximum index value for 2017 is 0.30; for 2020 it is 0.17. Minimum values are -0.72 and -0.74 respectively. The average value of the points is -0.45 for both years. The standard deviation is 0.19 for 2017 and 0.20 for 2020.

As can be seen from the NDWI maps, zero or positive humidity index values are characteristic of water areas (lakes, rivers) and high-altitude areas. Since waters or humid areas are assessed with the NDWI index, points are assigned up to a value of -0.2 (low-humid areas) to the same group when assigning categories. The number of these points was 3,191 in 2017 and 3,290 in 2020 (Table 3). As can be seen, there has been an increase in these areas. The increase in land acquired from NDWI at low index values can be seen as an example of the water shortage problem in the country in recent years. Thus, the reduction of precipitation in the country over the past few years, including in mountainous areas, is today's reality. Due to this, the volume of water in mountain rivers and lakes is decreasing. As a result, declining freshwater resources and water required for irrigation in the foothills, including plains, are factors that increase environmental stress (Mammadov et al. 2020). Given that ecosystems are interconnected in a chain, disruption of one natural process increases fragility and sensitivity in others.

There was a slight increase in the number of points receiving values between -0.2 and 0 for the fishnet area (from 484 to 590 points). These points are more characteristic of high mountainous areas and zones close to riverbeds.

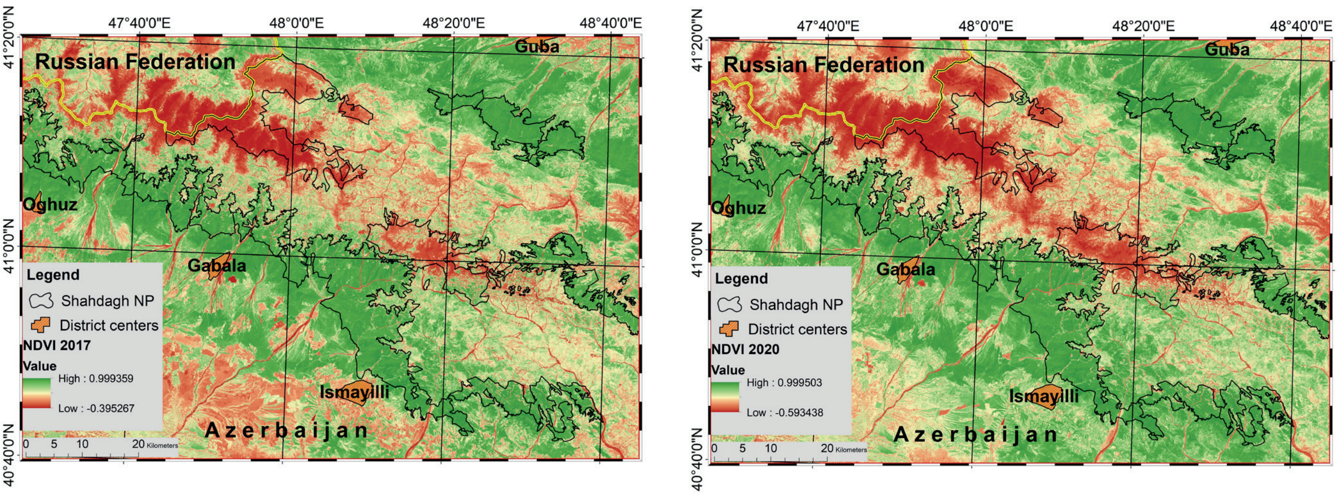

Fig. 3. NDVI maps obtained from Sentinel 2 images (2017 and 2020)

Table 2. The number of fishnet points matching the NDVI values

Ranges	Number of points by year	
	2017	2020
0 >	41	95
0 – 0.1	301	332
0.1 – 0.2	235	266
0.2 – 0.3	298	245
0.3 – 0.4	381	316
0.4 – 0.5	450	404
0.5 – 0.6	460	431
0.6 – 0.7	453	407
0.7 – 0.8	1120	979
0.8 <	86	350

But naturally, the area was recorded very few positive points. It should be noted that positive values are observed mainly in open water areas (Xu 2006). There is a slight decrease in the latter indicators (from 46 to 43). This shows that there is a slight change in the mountain lakes and riverbeds.

The next index calculated for the area during the study is NDDI (Figure 5). NDDI combines NDVI and NDWI data, which means using Green, Red, and NIR bands of the satellite images. The main purpose of calculating this index was to identify arid areas, which are one of the important factors to get information about fragile or more sensitive ecosystems. According to calculations, maximum and minimum values for these indices are 0.74 and -0.20 in 2017 and 0.75 and -0.13 in 2020, respectively, for fishnet points. The average value is the same (0.46) for each year.

However, some deviations were recorded in the obtained drought indices. Thus, the forest areas, which are mostly covered by Shahdagh National Park, received high values according to the NDDI. This gives a reason to say that errors occur when calculating the drought index for mountainous and forest areas due to the reflectance of the cover. For this reason, only the number of points below the average value of NDDI was calculated to avoid errors. According to the calculation, the number of points for 2017 was 1,646, while in 2020 it was 1,638 of them. Thus, it was determined that the areas with almost no drought indices decreased only slightly in these years.

In the study, there has also been calculated the range in which all three index values were most commonly obtained from fishnet. According to the designed boxplot (Fig. 6), most of the points for NDVI values vary approximately between 0.33 and 0.73 for 2017 and 0.31 and 0.75 for 2020. The boxplot shows that the range between the lower and upper quartiles in the NDVI slightly increased. In particular, a slight increase in the upper limit can be considered a positive development. Thus, despite the small difference between the studied years, the growth rate of green mass is observed for the study area. This positive result may be due to the strict observance of the security regime in the national park. Another indicator for the boxplot is NDWI values. Given that the study area is essentially mountainous, most of the values of NDWI get points below zero. It is due to the fact that only water areas can get above-zero values as discussed above. According to the boxplot, most NDWI points change from -0.34 to -0.6 for 2017 and from -0.32 to -0.62 for 2020. Finally, from this boxplot, most values of the NDDI index vary between 0.34 and 0.62 for 2017 and 0.31 and 0.63 for 2020. The extension of the lower NDDI limit should also be noted here as a positive nuance. The results of the NDDI were commented on above.

To illustrate the relationship between all indices, correlations have been identified and shown in Figure 7. The relationships allow determining and visualizing a correlation between pair of indices. The dots in a scatter plot report all the values. Scatter plots also show if there are any unexpected breaks in the data and if there are any exceptional cases. From these connections, the strong positive correlations between NDVI and NDDI for the same years imply the influence of anthropogenic impact on the ecosystem. Since human activities have greatly influenced the water regimes, the effects of droughts on NDVI need to be further studied. NDVI values between 2017 and 2020 and NDWI values between 2017 and 2020 are weakly positively correlated. The close values of correlations of NDVI indicate that variables are of similar significance in determining vegetation growth change. The relationship of other mixed indices is mainly weakly or strongly negative. It is clear that the correlation between NDWI and NDDI is strongly negative. It is because one of them is the index of water and the other is the index of droughts.

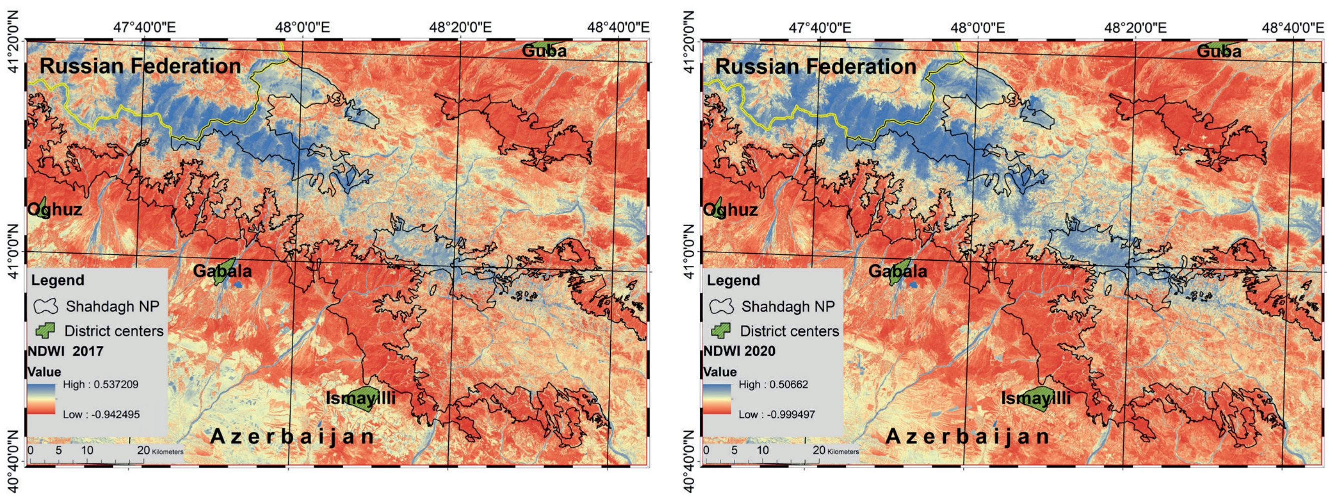

Fig. 4. NDWI maps obtained from Sentinel 2 images (for 2017 and 2020)

Table 3. The number of fishnet points matching the NDWI values

Category of values	Number of points by year	
	2017	2020
>-0.2	3,191	3,290
-0.2–-0.1	275	306
-0.1–0	209	284
0–0.1	37	40
0.1–0.2	9	3

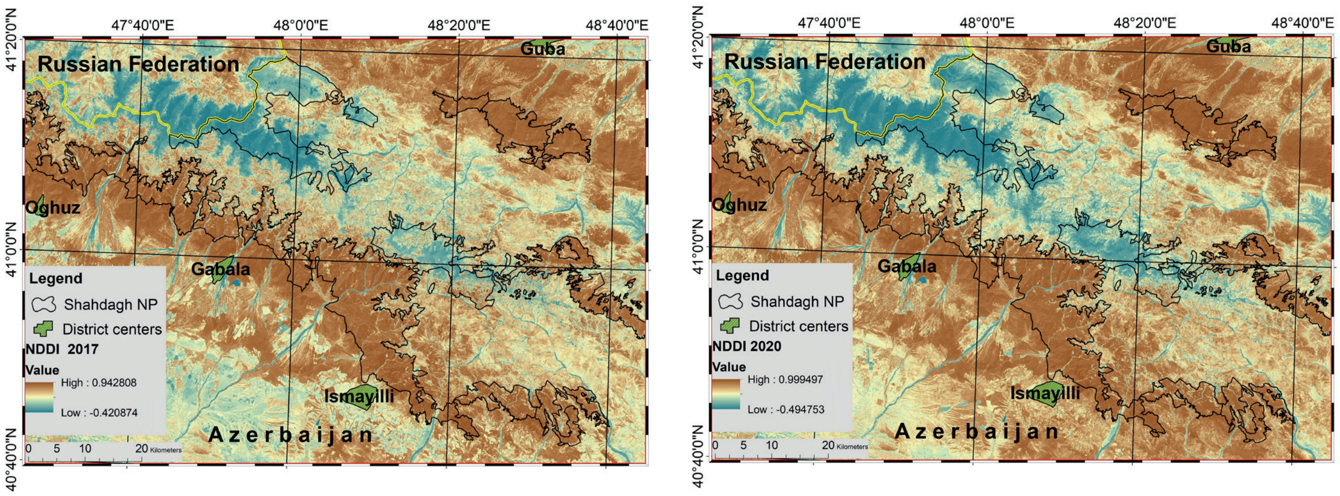

Fig. 5. NDDI values for 2017 and 2020

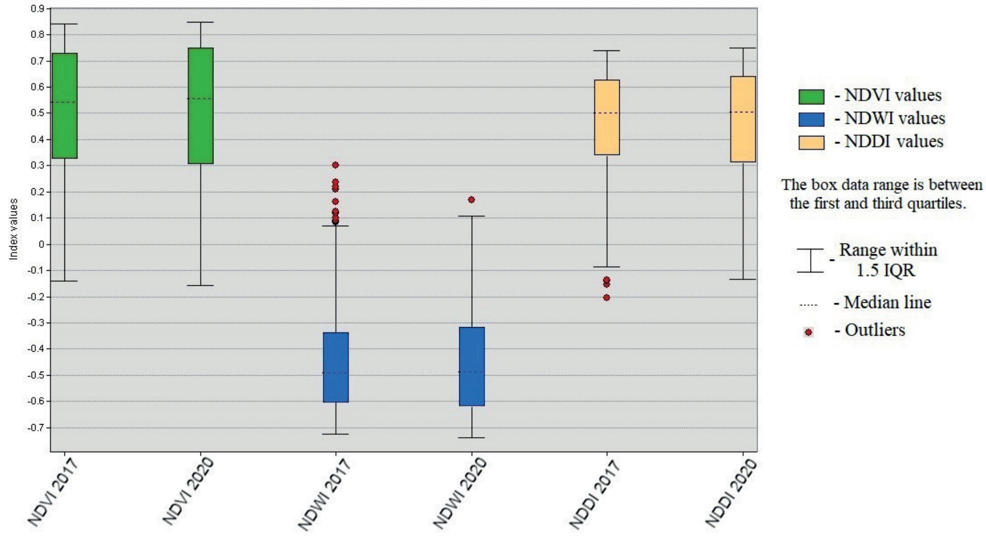

Fig. 6. Boxplot for NDVI, NDWI, and NDDI values

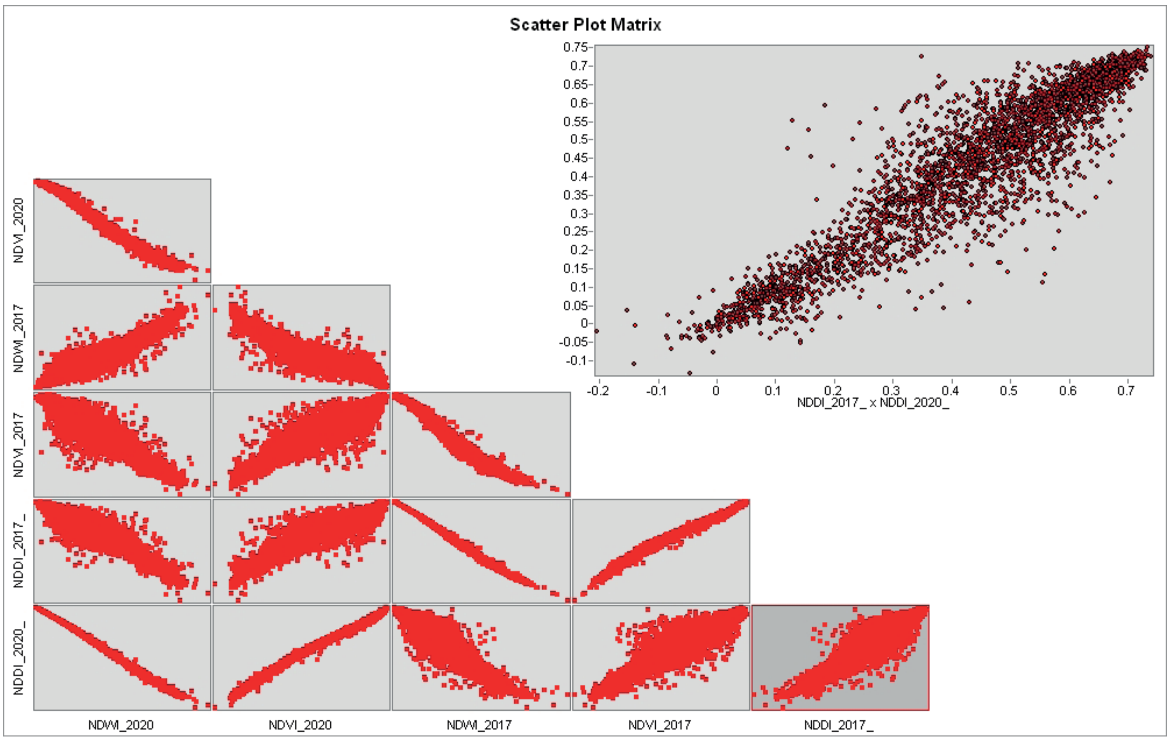

Fig. 7. Bivariate relationships of NDVI, NDWI, and NDDI indices

CONCLUSIONS

The study determined the environmental changes and monitored the recent remote sensing data for acquiring the relevant results. The environment has been properly monitored for defining fragile ecosystems and the methodology used for the study showed itself perfectly for obtaining for accurate results. The use of satellite-based indices allows for a clearer view of the relevant ecosystem indicators. It is reasonable to monitor the real-time state of the components of the environment, especially during the implementation of management and environmental impact assessment plans and programs, socio-economic activities, and strategies aimed at the development of local areas.

The use of formulas of the NDVI, NDWI, and NDDI gave relevant results for ecosystem quality assessment by Sentinel 2A multispectral image data. The results of the observation of degradation processes in low-lying areas and plains are concerning. Such areas are especially common for the national park. Thus, the results of anthropogenic impacts are visible in the surrounding areas of the national park, especially around the settlements and in the mountain meadows. This leads to the transformations and fragility of natural ecosystems in these areas. However, within the national park, the application of a special protection regime accelerates the process of natural recovery. The increase in dense forest ecosystems within the national park from 2.2% to 9.2% of the total can be considered a positive development. This is due to the serious and effective organization of the security regime in the national park. The increase in low-humidity areas or negative water index values from 83% to 86% is estimated to be the result of a decrease in precipitation observed in recent years.

As ecosystems are interconnected, the disruption of one natural component can lead to the degradation of others in a chain. Thus, the use of remote sensing methods allows detecting the changes in the environment in the study area, and initially assessing the risks associated with various impacts, considering future generations.

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