STUDY OF THE IMPACT OF CLIMATE CHANGE ON TOURISM ACTIVITIES USING REMOTE SENSING IN THE CARPATHIAN REGION

Mykola DEPUTAT[1], Khrystyna TERLETSKA[1], Vasyl ZHUPNYK[1], Pavlo HORISHEVSKYI[1], Dmytro KASIYANCHUK[2*]

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ABSTRACT

Climate change is having a significant impact on the tourism and recreational potential of the Ukrainian Carpathians, particularly in mountainous regions that rely on winter sports, hiking and ecotourism. Rising temperatures, decreasing snow cover and changing precipitation patterns threaten the viability of ski resorts and winter tourism. This study aims to assess the impact of climate change on tourism development in the Carpathians through remote sensing, GIS modelling and analysis of long-term climate data. The research is based on a comparative analysis of historical climate trends, satellite imagery and mathematical modelling of temperature and precipitation dynamics. Using Google Earth Engine and remote sensing techniques, key indicators such as snow cover area, albedo index and normalised difference snow index (NDSI) were analysed to assess changes in seasonal conditions. The results show a significant decrease in snow depth (approximately 4.4 mm per year) and snow-covered area (0.21% per year). The data indicate a shift in seasonality, a shortening of the winter season and an increase in climate-related risks to tourism infrastructure. Despite the negative impacts on winter tourism, climate change may increase opportunities for summer and autumn tourism, such as hiking and cycling. To mitigate these challenges, adaptation strategies need to be developed, including snowmaking technologies, diversification of tourism services, and sustainable environmental management. This study provides critical insights into the long-term dynamics of climate change in the Carpathians and supports strategic planning for sustainable tourism development.

Key-words: *Climate; Tourism; Snow cover; Geostatistics; Spatial analysis; GIS; Remote Sensing; Carpathians; Forecast.*

1. INTRODUCTION

Climate change is having a significant impact on winter tourism in the Carpathian region, especially in the context of decreasing snowfall, which makes ski resorts less attractive to tourists and less competitive. Winter tourism, and ski resorts in particular, are highly dependent on snowfall as it is the main natural resource that sustains the resorts during the winter season. Reduced precipitation in the form of snow leads to a shorter ski season, and in some places, there is not enough snow at all. Research shows that mountain landscapes and communities are particularly vulnerable to climate change, which has a direct impact on tourism.

In the Carpathian Mountains, an important mountainous region for Ukraine, rich in biodiversity, climate change is causing the winter tourist season to shrink, affecting infrastructure development and recreational opportunities. Climate change makes it impossible to plan new infrastructure facilities

[1]*Department of Tourism, Hotel and Restaurant Business, King Danylo University,Ivano-Frankivsk, Ukraine. (MK) mykola.m.deputat@ukd.edu.ua; (KT) khrystyna.m.terletska@ukd.edu.ua; (VZ) vasyl.v.zhupnyk@ukd.edu.ua; (PH) pavlo.gorishevskyy@ukd.edu.ua.*

[2]*Department of Geodesy and Land Management, Ivano-Frankivsk National Technical University of Oil and Gas, Ivano-Frankivsk, Ukraine. * Corresponding author: (DK) dima_kasiyanchuk@ukr.net*

for snow sports, and only two of the existing snow slopes (Bukovel and Dragobrat) are currently operating steadily. Resorts such as Bukovel and Dragobrat are focusing their efforts on using artificial snow to compensate for the lack of natural cover. Smaller resorts that do not have sufficient financial resources to provide artificial snowmaking cannot operate at full capacity, leading to less competition in the market. The introduction of snowmaking technologies makes it possible to extend the winter season even in the absence of natural snow, but requires significant capital expenditures, energy and water, which may pose additional environmental threats in the context of a shortage of natural resources due to climate change.

Tourism itself is also a significant source of greenhouse gas emissions, further exacerbating the problem of climate change. The impact of artificial snow on the ecosystem, including changes in soil and water resources, can have a negative impact on local biodiversity. In addition, artificial snowmaking is not only economically costly, but also changes the natural landscape of mountainous areas, which can have long-term consequences for environmental sustainability.

In light of these challenges, the question arises: how suitable will the climatic conditions remain for winter tourism in the Carpathian region in the coming decades? To address this question, it is necessary to develop effective adaptation strategies that take into account long-term climate projections. An important step in this direction is to analyse the impact of climate change on the seasonality of tourism and the quality of tourism services.

For this purpose, modern methods of geospatial analysis and satellite image processing are used. Modern geographic information systems (GIS) provide accurate information on the dynamics of snow cover, albedo and other climatic indicators, which allows us to create mathematical models to assess spatial and temporal changes in climatic factors and their impact on various aspects of human activity, including tourism. A large number of available remote sensing images are widely used to map snow cover in mountainous regions. This opens up new opportunities for a detailed assessment of the impact of climate change on the tourism potential of the Carpathian region and the development of strategies for the sustainable development of the tourism industry in the face of climate change.

The Carpathian tourist region (**Fig. 1**) consists of four districts in western Ukraine: Lviv, Ivano-Frankivsk, Zakarpattia and Chernivtsi. The Carpathian tourist region covers an area of 56,600 km^2, which is 9.4% of Ukraine's territory.

Reducing precipitation in the form of snow is an important aspect of ski tourism. Snow is the main natural resource that keeps ski resorts open in winter. However, the Carpathians, as an important mountain region rich in biodiversity, are increasinglay threatened by climate change (Turnock, 2001). Rising temperatures caused by climate change are leading to shorter ski season, and in some areas there is no snow at all. Research (Steiger et al., 2022) shows that mountain landscapes and communities are particularly vulnerable to climate change, which has a direct impact on tourism, and this is the basis for assessing the suitability of weather conditions, organising and planning tourism activities for outdoor recreation using the Holiday Climate Index (HCI) (Magyari-Sáska et al., 2023). Decreasing snow cover has a negative impact on winter tourism, while the impact on summer tourism may fluctuate. This can make ski resorts less attractive to tourists and less competitive. In addition, tourism itself is a significant source of greenhouse gas emissions, further exacerbating the problem of climate change (Steiger et al., 2023). One way to address these issues is to introduce snowmaking technology. This extends the skiing season even in the absence of natural snow. However, in order to develop effective adaptation strategies, it is important to analyse whether climatic conditions will remain suitable for tourism in certain regions and how they may change over time (Nistor et al., 2018; Kovács, Király, 2021).

The process of artificial snowmaking requires significant capital and energy costs and consumes large amounts of water, which can pose a threat to the environment, especially as natural resources become increasingly scarce due to climate change. The development of aerospace remote sensing and computer modelling of energy and mass transfer processes in the Earth's geosphere plays a crucial role in tracking these environmental changes and achieving sustainable development (Lyalko et al., 2022). Artificial snow can have several environmental impacts, including changes in soil composition and water resources, which can affect local ecosystems and biodiversity.

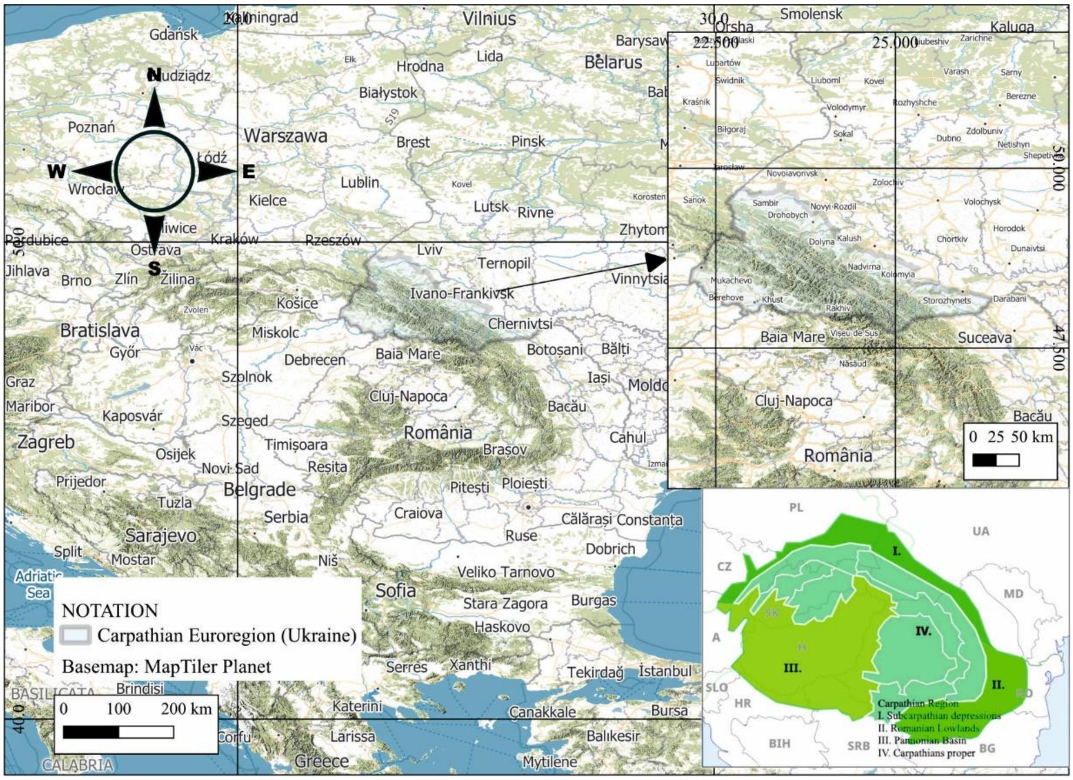


Fig. 1. Map of the Carpathian Euroregion study area within Ukraine (Basemap MapTiler, n.d.).

Remote sensing studies by Kulemin et al (2001) have shown that snow properties, including microwave backscattering properties, depend on many environmental parameters. A large number of available remote sensing images are widely used for snow cover mapping in mountainous regions. However, most studies have focused on quantifying the uncertainty inherent in snow mapping algorithms based on Landsat observations, especially in the context of snowline establishment, which is a key parameter for understanding the spatial and temporal dynamics of snow cover. The study (Xiongxin & Shuang, 2024) provides a comprehensive guide for selecting appropriate snow mapping algorithms and contributes to effective Landsat-based snow monitoring in mountainous regions. It is also worth noting that artificial snowmelt is not only economically costly, but also alters the natural landscape of mountainous areas and may undermine the sustainability of the ecosystem in the long term.

Climate change, changes in the regime of tourist complexes due to insufficient precipitation in winter, and human impact on landscapes are the main issues that require in-depth analysis and research. A detailed analysis of long-term observations of climatic parameters (air temperature, precipitation, duration of snow cover) should be carried out to identify key trends and their impact on tourism activities in the region. This allows us to assess the impact of climate change on the seasonality and quality of tourism services. Modern GIS technologies make it possible to interpret satellite image data for climate change analysis (Burrough, 2001; Odiljon, 2022). They provide accurate information on the dynamics of snow cover, the surface reflectivity index (Albedo) and other indicators that are important for developing mathematical models that allow assessing spatial and temporal changes in climate factors and their impact on various aspects of human activity.

The aim of this study is to quantify the impact of climate change on winter tourism in the Carpathian region of Ukraine, using geospatial analysis of satellite data and statistical modelling to assess changes in snow cover and predict long-term impacts on the tourism industry.

2. STUDY AREA DATA

2.1. Temperature and precipitation

The capabilities of the Google Earth engine, mainly satellite imagery data, allow us to cover a wide range of data that differ in their characteristics in our analysis. In recent decades, the impact on the environment of global temperature fluctuations has been increasingly associated with changes in the seasonality of the seasons. It is important to analyse long-term data of the main meteorological indicators at the initial stage. The period from 1980 to 2024 was chosen as the basis for the analysis. GEE is one of the most widely used methods for modelling.

Coding in JavaScript enables the analysis of available information based on satellite image decryption data.

The average monthly temperature changes fully characterise the main seasons ‑ spring (+1.0 ‑ +12.0°C), summer (+15.7 ‑ +17.1°C), autumn (+12.4 ‑ +1.2°C), winter (‑2.3 ‑ ‑3.0°C). However, if we look at the dynamic multi‑month values, we actually have a situation where the seasons are not so distinct, and seasonal factors can change.

Along with temperature (T), precipitation (P) must be considered. It is an integral part of the climate, especially in mountainous areas. As with temperature, we consider a series of monthly data averaged over many years of observations. Traditionally, the rainiest months are May (300mm), June (317mm) and July (256mm).

But it is important not only to consider seasonality, but also to identify the points of change between temperature and precipitation. According to the analysis, two points can be identified in the summer (first decade of June: T=+15.7° C, P=317mm) and autumn (second half of October: T=4.0° C, P=114mm). The rainy period clearly correlates with precipitation during the snowmelt period until June, and from the first half of the year in an opposite phase. July, August, and September de facto become a continuation of the summer season, and are characterised by low precipitation, which has a very negative impact on the hydrological balance of the region's rivers. This is confirmed by other studies (Pona et al, 2016; Kasiyanchuk, 2022). Mid‑October becomes the second variable stage between the short autumn period and the onset of cold weather. However, the decrease in air temperature does not lead to the active development of cyclones, and the amount of precipitation is insignificant. This dynamic has been particularly noticeable in recent decades.

Obviously, climate change is one of the main tasks for assessing the impact on the development of the region's tourism and recreational potential. Let's consider the basic seasonal characteristics, allocating summer (June, July, August), autumn (September, October, November), winter (December, January, February) and spring (March, April, May) in the traditional division (**Fig. 2**) with regression equations presented. The linear trend provides a simple and straightforward model for analysing long-term changes, estimating average annual growth and facilitating future forecasts.

Figure 3 shows the results of running a code that represents the long-term average of temperature and precipitation data from 1980 to 2024.

Air temperature as a basis for reflecting global trends is quite characteristic of them, as can be seen from the figure. All seasons show a clear increase in average annual temperature. The average annual temperature increase for spring is +0.041° C, summer ‑ +0.075° C, autumn ‑ +0.051° C, winter ‑ +0.073° C.

Frequent anticyclones that linger in Ukraine cause a decrease in precipitation in the form of rain and a slight increase in the form of snow (mainly sleet), as shown in the graphs in **Figure 3**.

Analysing the trend lines for the seasons, it can be concluded that precipitation decreases in spring, summer, and autumn, and slightly increases in winter. Reduced precipitation in the spring and summer, during the active growing season, negatively affects the microclimate of the region (Ivanyshyn, 2024).

The average annual precipitation is ‑1.1 mm in spring, ‑2.2 mm in summer, ‑0.2 mm in autumn, and +0.9 mm in winter.

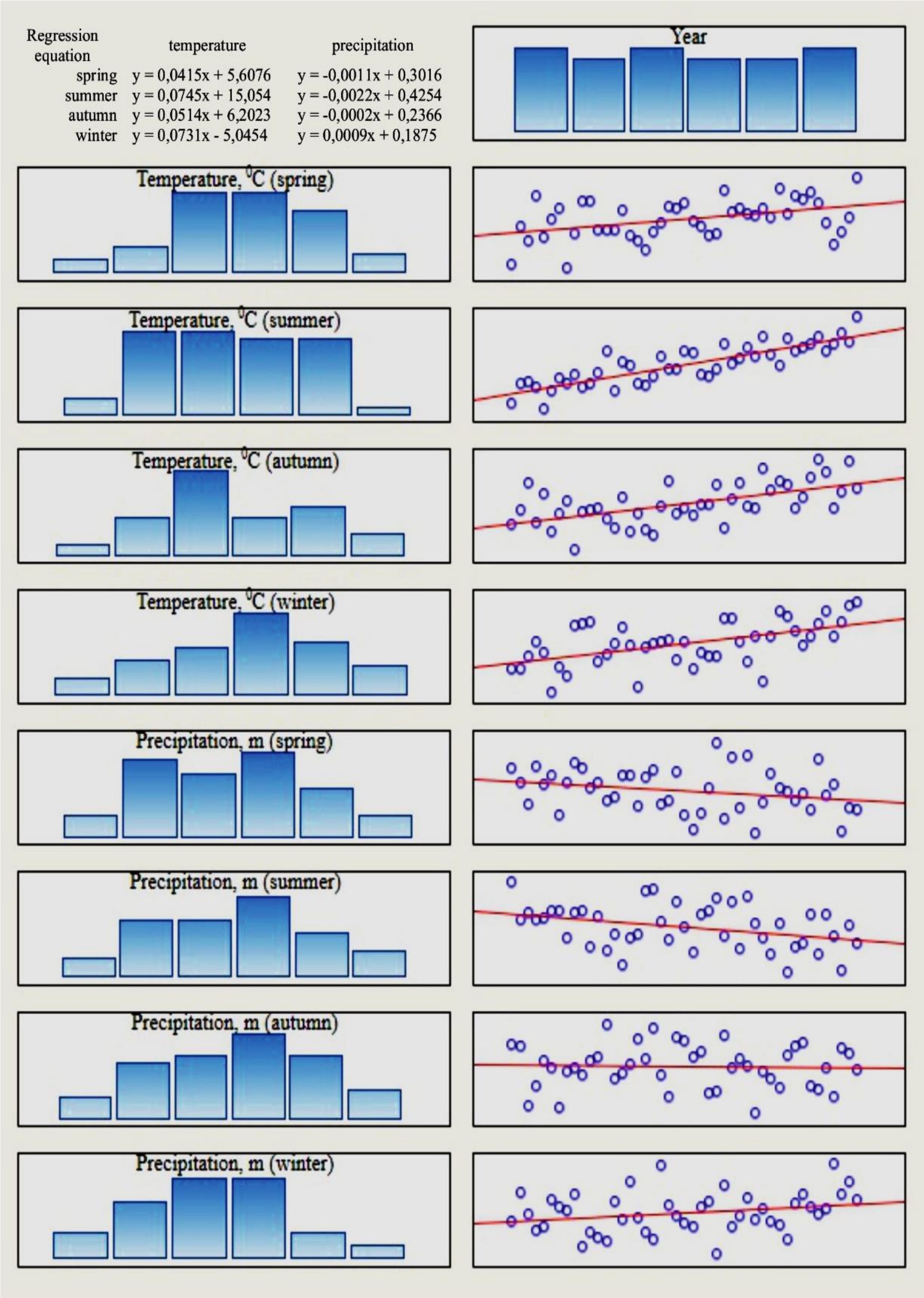


Fig. 2. Average long-term data from 1980 to 2024 by temperature and precipitation.

2.2. Snow parameters

The spatial and temporal variability of seasonal snow cover in mountainous regions is considered a significant knowledge gap in terms of climate, ecosystems and water resources (Gascoin et al., 2024). Three main elements where recent advances in remote sensing of snow and data accumulation promise to deliver significant gains include long-term observations of snow cover, including snow water equivalent, high-resolution snow cover and snow albedo. Various datasets have been used for analysis using the open-source Java Script, including ERA5-Land (Muñoz Sabater, 2019).

ERA5-Land is a reanalysed global atmospheric data set (climate and meteorological data) that has increased resolution compared to ERA5 and provides a consistent view of the evolution of land change over several decades. ERA5-Land was created by replicating the terrestrial component of the ECMWF ERA5 climate analysis. Reanalysis uses the laws of physics to combine model data with observational data from around the world to create a globally complete and consistent dataset. The reanalysis creates data spanning several decades, giving an accurate description of the climate of the past. This dataset includes all 50 variables available in the CDS.

2.3. Snow cover and NDSI

Matson's (1991) research includes comprehensive satellite studies since 1966 on snow cover. In the same year, NOAA satellites were used to produce weekly snow cover maps in the Northern Hemisphere. This 24-year database is available as a digital feed and is updated annually. The digital data can be used to calculate snow cover and create maps of snow frequency and anomalies. In (Wang & Wang, 2024) a new approach for snow mapping was developed using spectral feature fusion and correlation by integrating and analysing the Normalised Forest Snow Difference Index (NDFSI). Normalised Difference Vegetation Index (NDVI) and NDSI indices. High resolution OLI images from Landsat 8 were used to assess the accuracy of the snow maps. Experimental results show that the combination of NDFSI and NDVI indices has great potential for determining the distribution of snow cover in forested areas.

Table 1.

Bands of the ERA5-Land Daily Aggregated - ECMWF Climate Reanalysis.

Name	Units	Description
temperature_2m	*K*	The 2m air temperature is the interpolated temperature at 2 meters above land, sea, or inland waters, considering atmospheric conditions.
snow_cover	*%*	It represents the fraction (0-1) of a grid cell covered by snow, similar to ERA5 cloud cover fields.
snow_density	kg/m^3	Snow density represents the mass of snow per cubic meter in the snow layer, modeled in ECMWF IFS as a single layer over the uppermost soil level, covering all or part of the grid box.
snow_depth	*m*	Snow depth represents the instantaneous grid-box average of snow thickness on the ground, excluding snow on the canopy.
total_precipitation_sum	*m*	Accumulated precipitation includes liquid and frozen water, such as rain and snow, that reaches the Earth's surface. It consists of large-scale precipitation from weather patterns and convective precipitation caused by rising warm air. Precipitation is measured in meters as the depth it would have if evenly spread over the grid box, but observations may differ as they are often localized rather than averaged over a model grid.

2.4. Albedo

Another parameter is albedo, which is an important element in snow cover studies (Calleja, 2019; Laurin, 2022; Feng, 2023). MCD43A3.061 (Schaaf, 2021) is a MODIS (Moderate Resolution Imaging Spectroradiometer) satellite data product that provides daily land surface albedo data with a spatial resolution of 500 m. It is based on combined observations from the Terra and Aqua satellites. **Table 1** provides a list and description of the bands that will be used when writing the code.

3. METHODS

To achieve the main goal, namely modelling the impact of global climate change on tourism and resource potential, a number of steps need to be taken.

1. *Determination of the area* of the Carpathian Euroregion within the territory of Ukraine, which will serve as the basis for cartographic research:

- use of official geographic data (administrative boundaries, DEM models) to delineate the Ukrainian part of the Carpathian Euroregion;
- loading the relevant layers into QGIS and preparing the basic mapping material.

2. *The analysis of the main groups* of publicly available data in order to select the optimal ones in terms of factors and duration of observations should focus on:

- availability (NASA, ESA, Copernicus).
- duration of observations (minimum 20-30 years for climate trends).
- spatial resolution (optimally 250 m-1 km for regional analysis).

3. *Formation of file data* and further programming in the Google Earth Engine in JavaScript:

- uploading satellite data (Landsat, MODIS, Sentinel-2);
- using GEE to automate data collection, filtering, and pre-processing (scaling, normalisation, region cropping);
- creating JavaScript code to calculate time trends.

4. *Analysis of meteorological and climatic* parameters of the region:

- work with data from ground-based weather stations and reanalysis (ERA5);
- determining trends in temperature, precipitation, humidity and aridity index;
- creation of climate maps in QGIS.

5. *Construction of mathematical models* to assess the dynamics of temperature (T) and precipitation (P):

- using STATISTICA for cluster analysis;
- create a trend equation (1)

$$T(t) = a \cdot t + b \tag{1}$$

where:

$T(t)$ – the temperature in year t,
a – the slope coefficient (corresponding to the average annual temperature increase),
b – is a constant that determines the temperature level at the beginning of the period;

6. *Study of snow cover indicators* in the region and check the consistency of trends between different data groups:

- evaluation of MODIS (MOD10A1) and Sentinel-2 satellite data;
- checking the consistency of trends between different data sets.

7. *Calculation of the Albedo reflectivity index* and snow layer for areas with intensive development of winter sports:

- using Landsat-8 and Sentinel-2 data to calculate Albedo;
- analysis of changes in areas with a high concentration of winter resorts.

8. *Comparison of the relationship* between snow cover and the Albedo reflectivity index using STATISTICA (correlation analysis).

9. *Determination of the normalised* differential snow index (formula 2):

$$NDSI = (B3+B11) / (B3-B11) \tag{2}$$

where:

B3 (Green, 560 nm) – reflects snow well,
B11 (SWIR, 1610 nm) – is strongly absorbed by snow;

10. *Building maps of dynamic snow layer* assessment with comparison of snow cover data and Albedo index:

- creating maps in QGIS with comparison of snow cover and Albedo data;
- analysing changes in the territory over the decades.

4. RESULTS AND DISCUSSIONS

The Carpathian region is quite gradient in terms of climate and is characterised by altitude zonation. Given the main content of the paper, we decided not to divide it according to the stratigraphic basis, since long-term temporal changes will be the same for each zone, which is, in particular, summarised in Ivanyshyn (2024) and Shtohryn (2020). Changes in the seasonality of the seasons are extremely important, especially in reference regions that are important for the sustainable development of communities. The de facto shift, or rather reduction, of seasons from four to three (Kasiyanchuk, 2022), leads to sharp drops and sharp rises in temperature, and a clear division between seasons in long-term analysis is lost.

Analysing geospatial data using Google Earth Engine (GEE) (Gorelick et al., 2017) is done by writing code in JavaScript or Python to work with satellite images.

Code execution involves, first of all, a clear structuring of the main steps that will ensure the correct output:

1) Region Cropping. At the initial stage, all satellite images were cropped outside the study region to ensure that the analysis was carried out exclusively on the territory of interest. For this purpose, the `.clip()` function was used, which cropped the image according to the geometry of the selected area.

2) Image scaling (Scaling). Since data with different resolutions are used (Sentinel-2 with a resolution of 10-20 metres and MODIS with a resolution of 500 metres), the appropriate scaling was used to coordinate the calculations. The scale is set when calculating average index values.

3) Cloud Filtering. This step is described in detail below.

4) Normalisation of data. The Normalised Difference Snow Index (NDSI) was used to estimate the snow cover (formula 2). NDSI is calculated using normalised channel difference methods, such as normalisedDifference ().

5) Along with climatic parameters, it is important *to analyse the depth, area, and volume* of precipitation when studying snow cover. The software code uses ERAS-LAND data. Remote sensing capabilities are broad, but most limited by the level of cloud cover, which should always be taken into account when analysing for the purpose of correct interpretation. **Figure 3** shows the results of three characteristics - ‘snow_cover’, ‘snow_density’, ‘snow_depth’. Their detailed description is given in **Table 1**. As the results of the climate change study showed, with a clear increase in temperature and a decrease in precipitation, the most tourist-loaded mountainous area was chosen as the basis for further analysis in order to reduce the amount of additional calculations and detail the results within the tourist zones. The village of Polianytsia, the village of Verkhovyna, the city of Yaremche and the resort of Bukovel are known among a wide range of holidaymakers as the centre of active development of ski tourism and other recreational activities. The territory within these territorial units is defined as an active recreation area (ARA).

6) Analysis and removal of anomalies: During the results validation phase, additional analysis is performed to identify anomalous values (e.g., too low or high NDSI or albedo values that may be caused by residual clouds or other factors). Anomalies can be filtered out or corrected.

In contrast to the snow cover parameters, we calculated above, we will analyse two important indices, the 8-day average of snow area and Albedo (**Fig. 4**). The latter is an extremely important element of the study of snow cover, water bodies or any other objects with high reflectivity.

Figure 4 shows a graph that clearly indicates that both parameters are dependent, which is typical for the winter period. However, the data sample should be with 0% cloud cover within the study area (we do not exclude satellite images with a higher percentage of cloud cover).

Reducing the thickness of the snow cover changes the temperature regime of the soil, which affects the local flora and fauna, and reduces the supply of meltwater needed for aquatic ecosystems and river basins. This leads to the drying up of springs and disruption of natural hydrological cycles. In addition, snow plays an important stabilizing role, and a lack of it contributes to increased soil erosion.

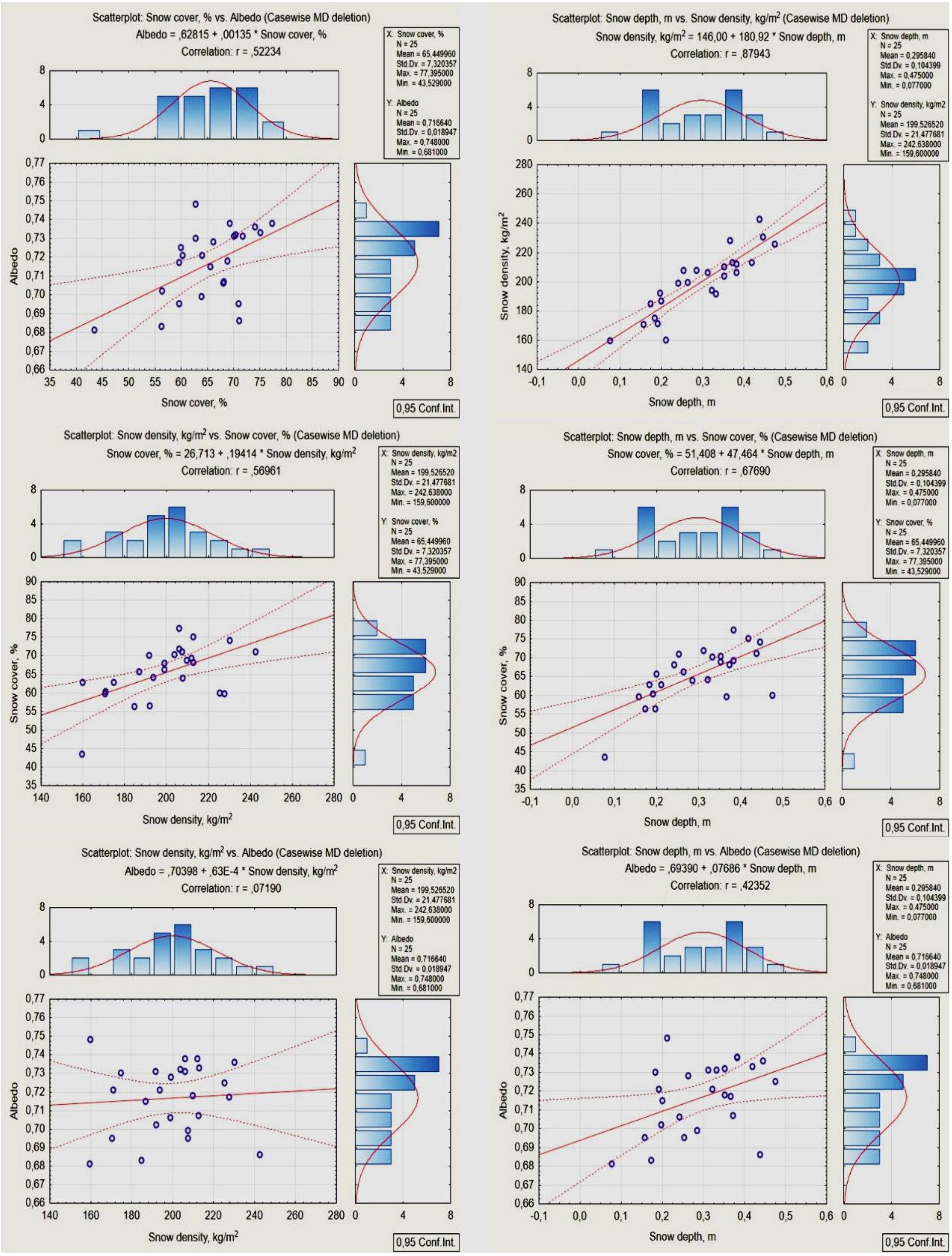
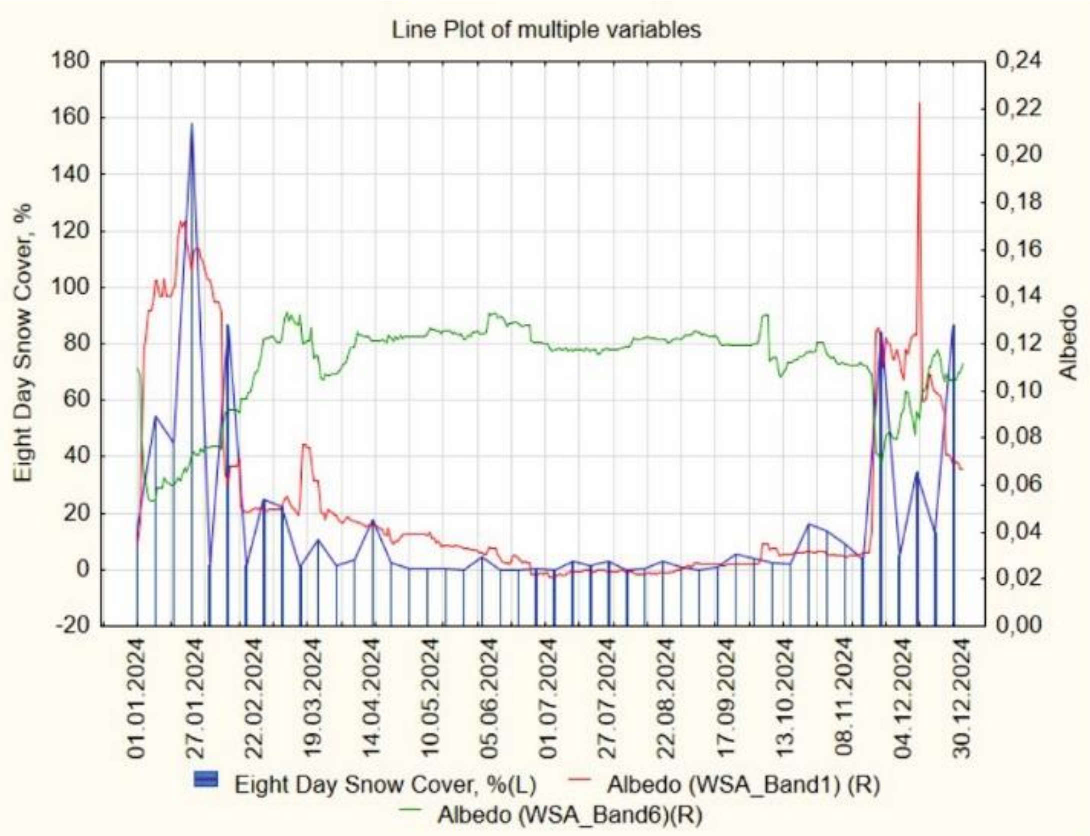


Fig. 3. Statistic of snow parameters from 2000 to 2024.



Variable	Color map of correlations N=46 (Casewise deletion of missing data) r>= -1 -0,80 -0,60 -0,40 -0,20 0 0,20 0,40 0,60 0,80 1 Eight Day Snow Cover, %	Albedo (WSA_Band1)	Albedo (WSA_Band6)
Eight Day Snow Cover, %	1,000000	0,628590	-0,642249
Albedo (WSA_Band1)	0,628590	1,000000	-0,881005
Albedo (WSA_Band6)	-0,642249	-0,881005	1,000000

Fig. 4. The 8-day average of snow area and Albedo.

In the tourism sector, a decrease in snow cover directly affects winter sports such as skiing and snowboarding. A shorter snow season reduces the profits of tourist complexes and affects local communities that depend on winter tourism revenues. In addition, deteriorating snow conditions may force tourists to choose other regions for their holidays, which will reduce the flow of visitors. In addition, changes in the structure of the snow layer may increase the risk of avalanches, which poses an additional threat to visitors and infrastructure. Thus, the decline in snow cover has a complex negative impact on both the environment and the economic stability of the region.

The resulting correlation coefficient of -0.64 between NDSI and albedo indicates a moderately strong inverse relationship between these indicators. This means that as snow cover decreases (lower NDSI), albedo also decreases, leading to greater solar energy absorption and accelerated snowmelt. This trend may contribute to a further reduction in snow cover in mountainous regions, which will affect the length of the winter season and the quality of the snow cover. For the future of tourism, this could mean a shorter period of winter sports, the need for artificial snowmaking and a general decline in the attractiveness of mountain resorts.

The European Space Agency has a wide range of Sentinel data. The most common way to analyse snow cover today is to estimate the Normalised Differential Snow Index (NDSI) (**Formula 2**). As mentioned above, the main thing in analysing satellite images is the absence of clouds. To compare the relationship between the NDSI and Albedo, the corresponding snow index maps were constructed (**Figure 5**).

In **Figure 5**, **Table 2**, we see the results of snow index decoding for two dates - 26.11.2024 and 28.12.2024. The average NDSI for the ARA is -0.079 and 0.03. On the map, the corresponding colours are interpreted as: black (-1) → no snow, blue (0) → partially snowy surface (coniferous forest zone), white (1) → snow.

For most of the bands (Band1-Band4), albedo significantly decreased from 26.11.2024 to 28.12.2024, Band5 remained almost unchanged, Band6 decreased significantly, and Band7 decreased slightly, but not significantly. While the first one gives us an idea of the vegetation, dense coniferous forests (Ivanyshyn, 2024), channel 6 clearly shows a change in reflectivity that has increased, which corresponds to an increase in snow mass, as shown in **Figure 5**.

The index map for the two dates gives us a clear spatial representation of the snow cover. The decoding allowed us to clearly show the differences between the indices and estimate that as of 28.12.2024, the snow cover was more significant, covering not only the tops of the mountains, but also the areas where ski resorts are located (central part of the ARA). This is where Bukovel is located, as well as some ski lifts in Yablunytsia and Vorokhta.

Data uncertainty is one of the most important limitations in satellite imagery, and the resolution, atmospheric conditions and time interval of the survey can affect the accuracy of the study. When generating the code using the methods described above, these uncertainties were minimised in order to accurately calculate the indices. The only drawback is that the limited frequency of image acquisition does not allow for the assessment of short-term changes in snow cover, which is important for detailed local monitoring and would require additional ground observations.

The importance of understanding the relationship between the parameters defined above is the main element that allows machine learning methods to be used for snow cover assessment. The written code implements a comprehensive approach to satellite image analysis using the Google Earth Engine (GEE) platform. The aim of the work is to classify the land cover in a given study area using Sentinel-2 multispectral data, MODIS temperature data, and the SRTM digital elevation model for snow cover assessment. The main classification tool is the Random Forest algorithm, which allows to effectively take into account various spectral and geophysical characteristics of the surface.

Table 2.

Average albedo value for each band and NDSI by date.

Albedo (Bands) / NDSI	**Date**	
	28.12.2024	**26.11.2024**
Band 1 (Visible Red, 620-670 nm) – displays the red part of the visible spectrum, which is important for studying vegetation	76,111	132,977
Band 2 (NIR, 841-876 nm) – reflects the near-infrared part of the spectrum, which is often used to study water stress and vegetation indices	219,268	263,218
Band 3 (Blue, 459-479 nm) – is used to assess water and atmospheric quality	62,512	126,887
Band 4 (Green, 545-565 nm) – important for studying vegetation	80,692	138,316
Band 5 (NIR, 1230-1250 nm) – helps to assess soil moisture and plant health	195,954	190,526
Band 6 (SWIR, 1628-1652 nm) – used to study snow cover and soil moisture	122,902	89,930
Band 7 (SWIR, 2105-2155 nm) is sensitive to water, important for monitoring glaciers and the water cycle	47,595	43,073
NDSI	0,030	-0,079

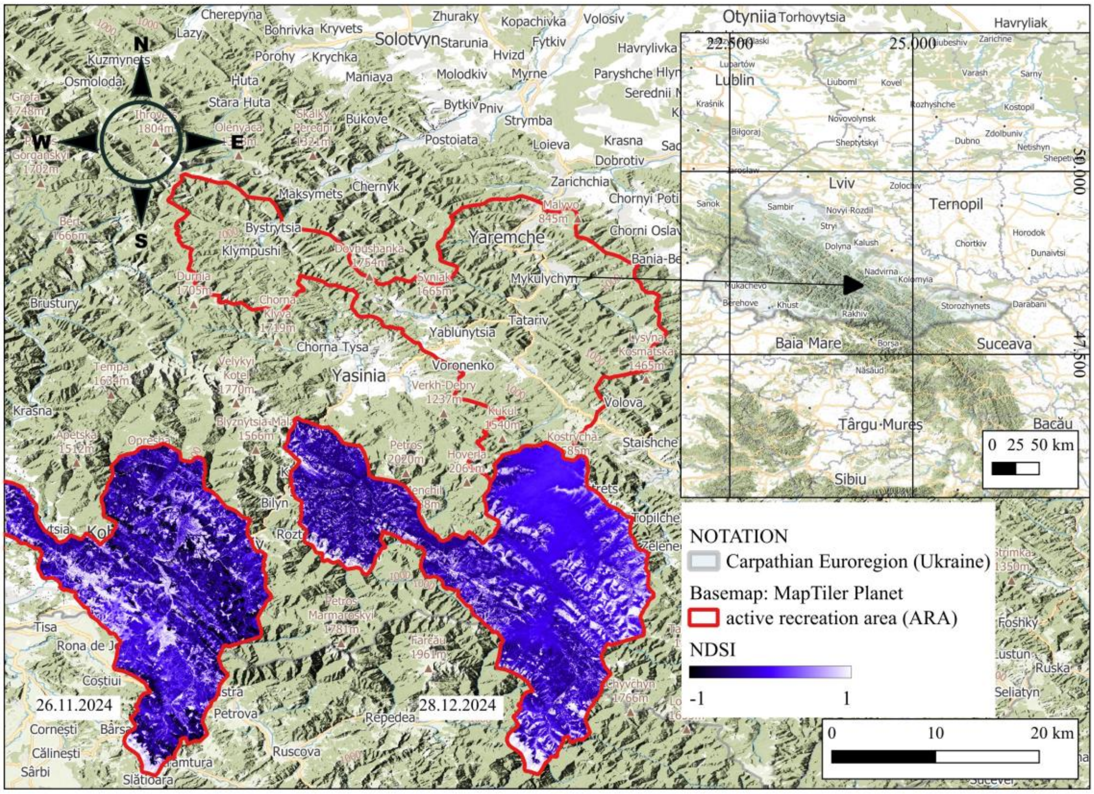


Fig. 5. NDSI map of the active recreation area (ARA) (Basemap MapTiler, n.d.)

At the first stage of the work, the study area is loaded, which is represented as a vector layer (FeatureCollection). This area is used to filter satellite images by geographic boundaries. Sentinel-2 data is loaded for a specific date, namely 28.12.2024, with the percentage of cloud cover taken into account to ensure the quality of the analysis. In addition, MODIS data is loaded to obtain the daily average surface temperature (LST) and SRTM data to obtain information on the height above sea level.

The next step is to calculate spectral indices that allow us to identify key characteristics of the land cover. In particular, we calculate such indices as NDSI (Normalised Difference Snow Index) to detect snow cover, NDVI (Normalised Difference Vegetation Index) to assess vegetation, and NDWI (Normalised Difference Water Index) to detect water bodies. Surface albedo from MODIS data is also loaded, which allows to take into account the reflectivity of the study area. Based on the calculated indices, masks for water bodies and healthy vegetation are created and used for further analysis.

To classify the land cover, a data stack is formed, which includes Sentinel-2 spectral channels, calculated indices, MODIS temperature data and elevation data. This stack is used to prepare the training data, which is generated by sampling pixels from a given geographic area. The Random Forest model is trained using 100 trees and 10 variables for each split. After the model is trained, the image is classified and the results are visualised on the map (**Fig. 6**).

The Random Forest model provides several important additional insights for analysing snow cover and land cover in general. Firstly, it allows to effectively take into account multidimensional spectral and geophysical characteristics, which improves classification accuracy. Secondly, the model provides an assessment of the importance of each feature (e.g., spectral channels, height, temperature), which makes it possible to understand which parameters have the greatest impact on the final classification.

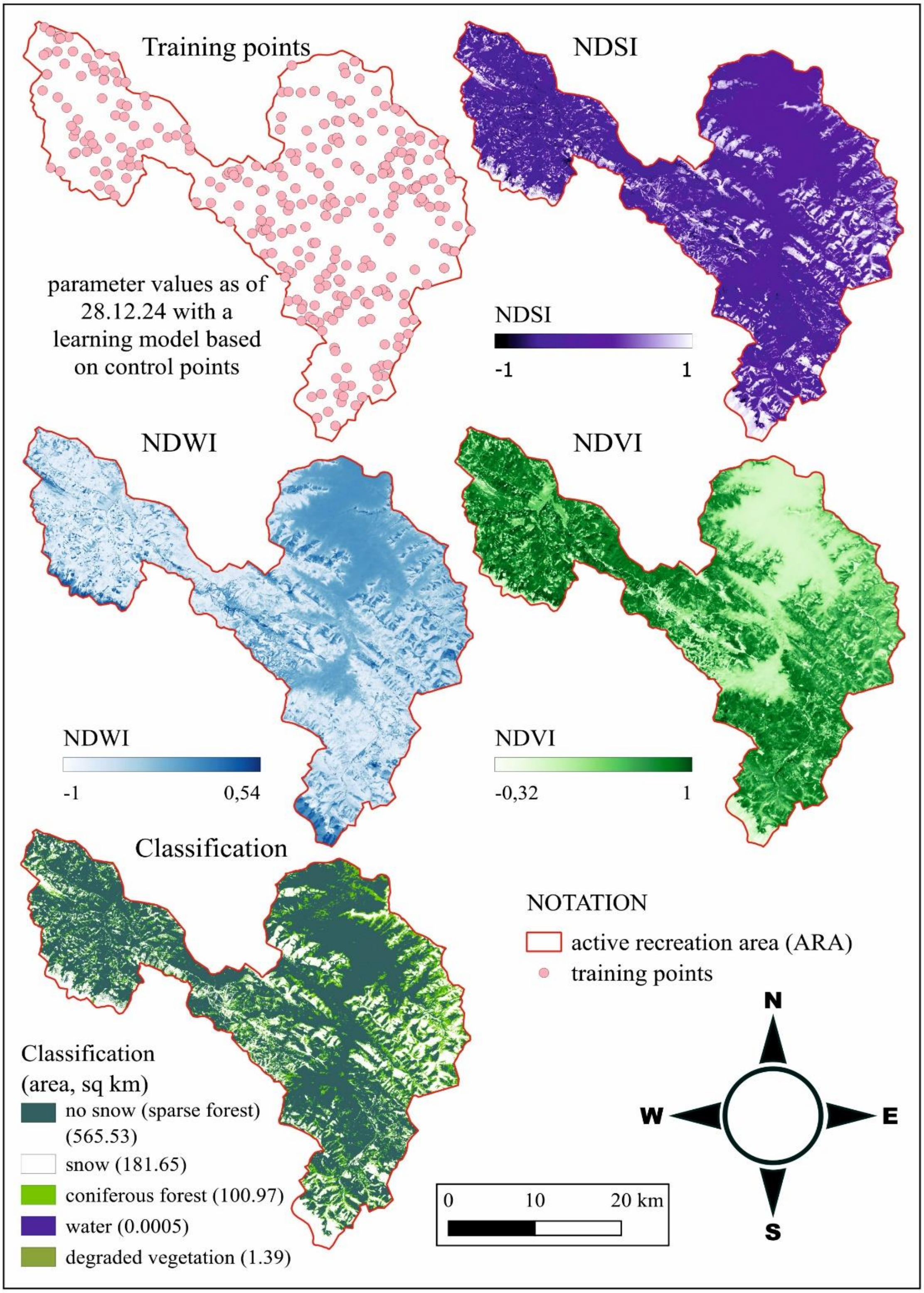


Fig. 6. Machine learning model based on Random Forest (RF).

Thirdly, Random Forest makes it possible to evaluate the accuracy of the model through Out-of-Bag (OOB) errors, which provides an independent measure of model quality. It is also possible to model the change in accuracy when each variable is changed, which helps to optimise the choice of parameters for classification.

In order to assess the quality of the model, a feature importance analysis was performed to determine the contribution of each variable to classification accuracy. In addition, the Out-of-Bag (OOB) error was estimated, which is a measure of the model's accuracy based on data that was not used during training. For a more detailed analysis of the impact of each feature on the model's accuracy, we implemented a simulation of the Mean Decrease in Accuracy method. This method allows you to assess how changing each variable affects the overall classification accuracy.

Based on the results of training a model that included 100 points divided into 10 subclasses, the generated sample allowed us to achieve a high level of training accuracy. More than 72% of the training points were correctly classified and showed good results, as we not only estimated the snow area, which is more than 21% of the study area, but also found that there are clearcuts on the study area of 1.39 km^2 (0.2%).

5. CONCLUSIONS

Climate change will have a significant impact on the tourism and recreational potential of the Carpathian Mountains, especially on winter tourism, eco-trails and water tourism. Rising temperatures and changing climatic conditions may shorten winter seasons, reduce snow cover, alter ecosystems, and reduce the attractiveness of recreational destinations and eco-trails. To sustainably develop the region's tourism potential, it is necessary to adapt infrastructure, protect natural ecosystems, and develop and invest in new forms of tourism.

The capabilities of Google earth engine, and especially satellite image data, allow us to cover a wide range of data in the analysis, which are different in their features.

The main results of the work include:

1) The increase in average annual temperatures (0.73 degrees per decade) and the decrease in snowfall have a negative impact on winter tourism, particularly on ski resorts.

2) Climate change is causing a decrease in snow cover by ≈4.4 mm annually, and the area of snowy areas is shrinking by 0.21% per year, making winter tourism in the Carpathians, especially in lowland resorts, increasingly less sustainable and could make ski tourism impractical over the next 40 years without appropriate adaptation measures.

3) Changes in climatic conditions lead to a decrease in the clear separation of seasons, which affects the periods of tourist activity. A gradual shift in seasonality and a reduction in the length of winter have been identified.

4) Satellite imagery and indices (NDSI, Albedo) have proven to be highly effective in monitoring climate change. The use of Google Earth Engine data allowed for a detailed assessment of the dynamics of temperature, precipitation and snow cover.

5) The use of the Random Forest algorithm allows to effectively take into account various surface characteristics, which makes this approach useful for solving a wide range of tasks in the field of remote sensing, accurately classifying more than 72% of the training points.

Although winter tourism is experiencing negative changes, the growing popularity of activities such as hiking and cycling may partially offset the losses. To maintain the Carpathian Mountains' tourist attractiveness, it is important to develop adaptation measures, including investments in alternative types of tourism, sustainable water and ecosystem management practices, and the development of artificial snowmaking. This will help to ensure a balance between environmental sustainability and economic development, as well as preserve the attractiveness of the Carpathians as a tourist and recreational region in the face of climate change.

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