DATA INTEGRATION FOR ENVIRONMENTAL MAPPING AND MONITORING IN SOUTH TYROL

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Abstract

This study has presented the estimate of the catchment-level water balance by assessing components separately using different field methods of a subalpine forest in South Tyrol region (north Italy). The techniques of geospatial analysis, statistical modelling and mapping were used for analysis of environmental and hydrological variables in coniferous forest. Methods - tools included data integration, processing and modelling. Techniques employed eddy covariance (EC) of tree transpiration sensors, phenocam images, throughfall and stemflow gauge. These instruments were employed to measure water discharge, soil humidity, and quantify moisture in epiphytes. After data collection, the data were modelling using Python-based statistical libraries. The aim was to monitor a dense old (>200 years old) and young (<30 years old) forests in different seasons (wet and dry periods) in order to compare their effect on water balance. The study is located in South Tyrol. The cumulative effects of climate and environmental change were quantified by environmental habitat assessment. The resistance of young and old forests to climate effects was analyzed on landscape level. Environmental monitoring is a key tool for understanding the climate challenges in forest ecosystems. The results revealed that the age of trees and availability of lichens on the trunks contribute to water balance through increased humidity and interception of water by canopy. This study contributes to environmental analysis of climate-hydrological dynamics of mountain habitats in north Italy.

Key words: Environment, climate, hydrology.

JEL[2]**:** Q23, Q24, Q25

Introduction

Environmental monitoring of rural areas is crucial for estimating ecological parameters, water balance, and accurate meteorological predictions (Martać et al., 2021; Stajić et al., 2022; Lemenkova, 2022a; Mladenović et al., 2024; Lemenkova,

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2025a). The prevailing method combines modelling data with spatially continuous variables (Bobinac et al., 2016; Šurjanac et al., 2020; Lemenkova, 2024a; Popović et al., 2025). However, these models often overlook forest growth variables and face challenges with geolocation errors. To fill in this gap, this study introduces a technique to screen for correlations between the environmental and climate parameters using statistical and GIS mapping techniques.

With an influence that extends well beyond their real range, mountain regions are crucial for the availability of water (Eremija et al., 2019; Marković et al., 2019; Lemenkova, 2021; Lemenkova 2022b; Matović et al., 2024; Lemenkova 2024b). But, with historical and anticipated warming above the world average, they are also heavily impacted by climate change. Subalpine regions in the Alps are fragile ecosystems with high importance for water and land resources and local climate. While previous studies have measured different components of the water balance (Dhingra, Chaudhary, 2011; Nikić et al., 2012; Marković et al., 2021), no studied are presented using data integration that combines climatic and ecological datasets and mapping for South Tyrol.

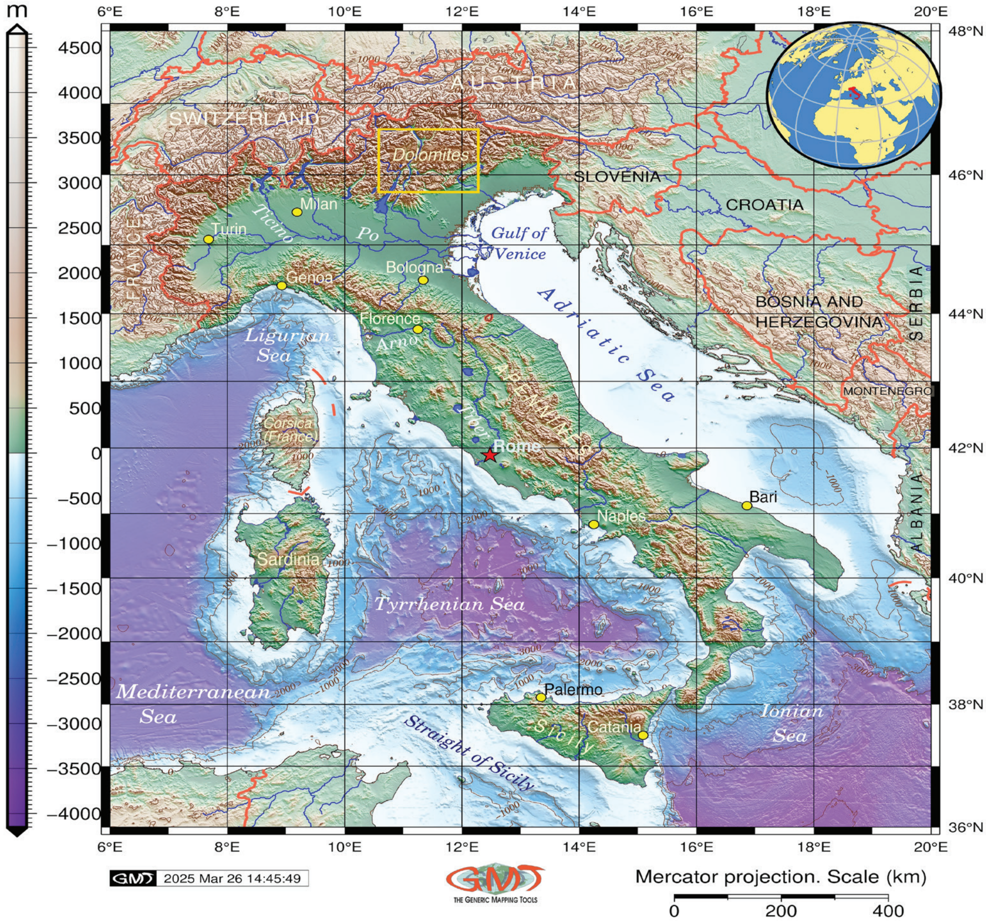
Environmental and climate factors like temperature, evapotranspiration, and rainfall have influence on rural sustainability and land resources (Contandriopoulos, Gamisans, 1974; Latocha et al., 2018). Regional variations in rural habitat suitability across Italy face challenges due to climate factors and human-induced activities, such as decrease of runoff in selected subalpine areas (Brooks et al., 1994; Durka et al., 1999).

Alpine regions experience different effects from warmer temperatures, such as enhanced radial growth (Holko et al., 2024), which may require enough water availability to offset the increased evapotranspiration (Mikac et al., 2013). Therefore, in order to forecast the effects of future climate change, moisture availability must be considered for environmental prognosis and assessment. In addition to have a negative impact on livelihoods and perhaps resulting in human mortality, forest misuse and degradation can create environmental issues such soil erosion, landslides, rockfalls, increased water runoff or decreased water storage, dryness and biodiversity loss.

Objectives and Goals

The objective of this study is to estimate water balance and all of its components in subalpine forest in the Central Italian Alps (South Tyrol). Specifically, the study considers environmental factors, such as fog appearance, tree heights and age. The region of the study is located in South Tyrol, north Italy (Figure 1.).

Figure 1. Location of the study area, South Tyrol, north Italy



Source: Software - Generic Mapping Tools (GMT), version 6.5.0

Water balance is among the most important parameters of the environmental health in forests. Changes in water balance (wet or dry periods) significantly affect environment, ecosystems and vegetation. The analysis of hydrology of the coniferous forests is a background for prognosis of environmental dynamics. At the same time, environmental data modelling requires the use of the advanced software for effective processing of collected data using statistical approaches. This is possible using Python programming tools and libraries (Lemenkova, 2025b). Modelled data presented on graphical output enable to reveal correlations between parameters, recognize dynamics and interpret major trends between environmental and climate parameters. In turn, such data represent valuable information for forecasting in silviculture and environment modelling.

This study also investigates the impact of moisture (precipitation during rainy days) on canopy in forests of different age and height. Water distribution in forests and its effects on land-use management, water policies, and climate system are still poorly understood. In this way, performed study contributes to the missing gap in research on eco-hydrology of subalpine forests. The assessment of evaporation fluxes, that involve significant uncertainty, while challenging to evaluate and understand, is thus impacted by these huge fluctuations in cloudiness at tiny scales. The meteorological data also shows that there were 111 cloud-free days and 254 days with air turbidity.

An essential but frequently overlooked component of the mountain water balance is the flora of mountain regions, whose distribution is determined by complicated (micro)topography, and changes in soil and climate along elevation gradients. Convective clouds that form above peaks in the summer and thermal inversions that cause more fog to form in valleys in the winter are two factors that affect the environment of the Alpine region. Coniferous forest of natural origin is located in Italian Dolomite Mountains. This region is essential source of water provision with an impact extending far wider than their actual range. However, the forests are also strongly affected by climate change with past and projected warming, exceeding the global average. The vegetation of mountain regions in north Italy is affected by the change of climatic and soil conditions along elevation gradients and complex topographic settings. In the Dolomites and other Central European mountains, the subalpine elevation belt is mostly covered by forests dominated by conifers managed for wood production.

The tree layer (diameter at breast height (DBH) > 5 cm) consisted of 85% spruce [*Picea abies* (L) Karst.], 12% Swiss stone pine (*Pinus cembra* L.), and 3% European larch (*Larix europea* L.) trees. Scots pine (*Pinus sylvestris* L.) and European rowan (*Sorbus aucuparia*) individuals were also present sparsely. The dominant tree height was approximately 29 m. The understory consisted of alpenrose (*Rhododendron ferrugineum* L.), blueberry (*Vaccinium myrtillus* L.), and intervening grasslands, e.g. wavy hair-grass [*Deschampsia flexuosa* (L.)].

Materials and Methods

Operative modelling and monitoring of landscape resources is essential for proper land management and socio-ecological sustainability. Landscape is essential to the human well-being as a habitat and natural resource. At the same time, landscapes are affected by ecological and climate processes. The health of landscapes can be resumed as regional environmental sustainability. Analysis of land cover changes and responses of vegetation to climate factors is necessary for sustainable development

(Zhang et al., 2011; Loehman et al., 2011; Klaučo et al., 2017). With ecological changes affecting regional development, assessment of environmental and climate parameters becomes essential (Klaučo et al., 2013; Wang, Fensholt, 2017; Dubeau et al., 2017). To evaluate forest stands, the fieldwork was performed for comparison of old and young forest trees and their role in water balance. The traditional fieldwork observation involved the thinning of the surrounding trees (Li et al., 2025; Zhu et al., 2025). The result is a heterogeneous vegetation structure, with groups that are almost even-aged forming an uneven-aged structure at a larger scale. A large group of dominant spruce old trees (>200 years old), and a second group of young trees (<30 years old) were present at the study site. In both stands, parts of the living crown frequently reached the ground.

Evapotranspiration was assessed by the eddy covariance technique (Zhang et al., 2025; Wang et al., 2025). The measuring system was composed of a 3D ultrasonic anemometer (Hollenbeck et al., 2025; Liu et al., 2025), and an enclosed-path infrared (IR) gas analyzer (Khan et al., 2022). The instruments were placed on a tower at 33.7 m above ground level. Taking of air samples were done through insulated steel tube, that has 4 mm internal diameter, as well as 0.75 m in length, while set at 0.15 m from anemometer. Setups followed the ICOS standard. Raw CO_2 and H_2O concentration values, as well as 3D wind speed have been measured at 20 Hz. It has to be underlined that fluxes were computed and logged every 30 min and processed in Eddypro software. The correlations between variables are modelled in graphs by Python.

Accurate modelling and mapping techniques were applied using Python to evaluate correlations between the data (Lemenkova, 2019; Lemenkova, 2020). By measuring and contrasting water interception, epiphyte composition, and temperature at various elevations with a nearby young canopy forest, the impact of older tree vegetation on water balance was studied. Eddy covariance and transpiration using sap flow sensors were used to measure evapotranspiration and environmental parameters: relative humidity (RH), vapor pressure deficit (VPD), and air temperature (T), Table 1.

Table 1. Sensor position for environmental parameterization of T, RH, and VPD

Sensor position	T (°C)	RH (%)	VPD (hPa)
Outside	11.0 ± 4.8	77.5 ± 16.6	3.46 ± 3.30
15 m	11.5 ± 5.3	89.1 ± 14.2	2.02 ± 3.28
23 m	12.4 ± 6.2	82.7 ± 17.5	3.56 ± 5.13

Source: author development.

Soil moisture was assessed in old and young forest with additional soil-level measurements. Water discharge was measured during fieldwork at catchment level. Precipitation below the canopy as throughfall was measured with sixteen manual rain gauges, arranged in two groups of eight in the two main forest formations, the 200-year-old section and the 30-year-old section. These pluviometers, with a 10-cm diameter orifice, were arranged in rows with a 5 m distance between each one, and data were recorded almost on a weekly basis.

Fog and mixed precipitation were collected by a fog and mist passive collector and pluviometer (Kathiravelu et al., 2016; Reboita et al., 2024). The role of fog was estimated by its impact on throughfall. A correlation between throughfall and precipitation was determined for mixed precipitation and rain-only events for young and old trees. Using Python, throughfall was calculated for a precipitation period with rain only and during mixed periods. Fog contribution to throughfall for mixed precipitation days was estimated as the difference between measured throughfall and the contribution of rain to throughfall.

Soil water content was measured continuously within the site. Variations in its water content were calculated from beginning until the end of measuring time and the hydrologic year. Water discharge at the catchment scale was measured using a combination of a water stage sensor and flow velocity measurements. The water stage sensor was placed at the lowest spot of the catchment, just above an artificial water basin (46°35′00″N, 11°26′02″E, and 1,675 m a.s.l.), and measured the height of the water table in the stream (S in cm).

Soil water content (SWC) was quantified by the measurements done by time domain reflectometry (TDR) sensors. The sensors were placed in two locations, termed continuous plots according to ICOS protocol, one in a dense forest patch and the second in a clearing. The sensors were placed at either location, at depths 5, 10, 20, 50 and 100 cm below the litter layer. The volumetric water content variation in the first meter of depth was quantified by averaging the SWC at the different depths, linearly interpolating the values obtained and then assessing the SWC difference by subtracting the resulting water amount from a given water amount at the time of next measurement. The value obtained is expressed in terms of water volume then related to the corresponding surface.

Results and Discussion

The results shown that compared to old forest, young vegetation had lower transpiration. At the study site, there were two groups of spruce coniferous trees: a huge group of dominant trees that were ca. 200 years old trees, and a group of young trees in forest were ca. 30 years old trees. Water balance is influenced by soil and evapotranspiration. In precipitation occurrences that combined fog and rain, fog increased throughfall. The annual hydrological balance was impacted by discharge and change in soil water content. The coniferous landscapes have natural characteristics of forest stands managed for the wood production. The conventional harvesting technique thins trees and leaves with 50 m gaps. The vegetation has heterogeneous structure, with even-aged clusters producing an uneven-aged structure on a broader scale. In trees of both age categories (young and old), some canopy touched the ground. Water storage capacity of lichens was evaluated by meteorological characteristics (T, RH, and VPD) from 30 min data outside and inside canopy (15 m and 23 m at the top of canopy), Table 2.

Table 2. Climate parameters and vegetation responses

Days with mixed precipitation	Young forest	Old forest
P measured (mm)	460 ± 35	460 ± 35
Total Tf measured (mm)	292 ± 26	216 ± 11
Tf estimated from rain only events (mm)	243 ± 7	184 ± 8
Fog contribution in mixed events (mm)	70 ± 15	53 ± 5
Measured Tf/P (%)	64	47
Estimated rain-only Tf/P (%)	53	40
Estimated fog Tf/P (%)	15	12
Rain contribution to Tf (%)	83	84
Fog contribution to Tf (%)	24	24

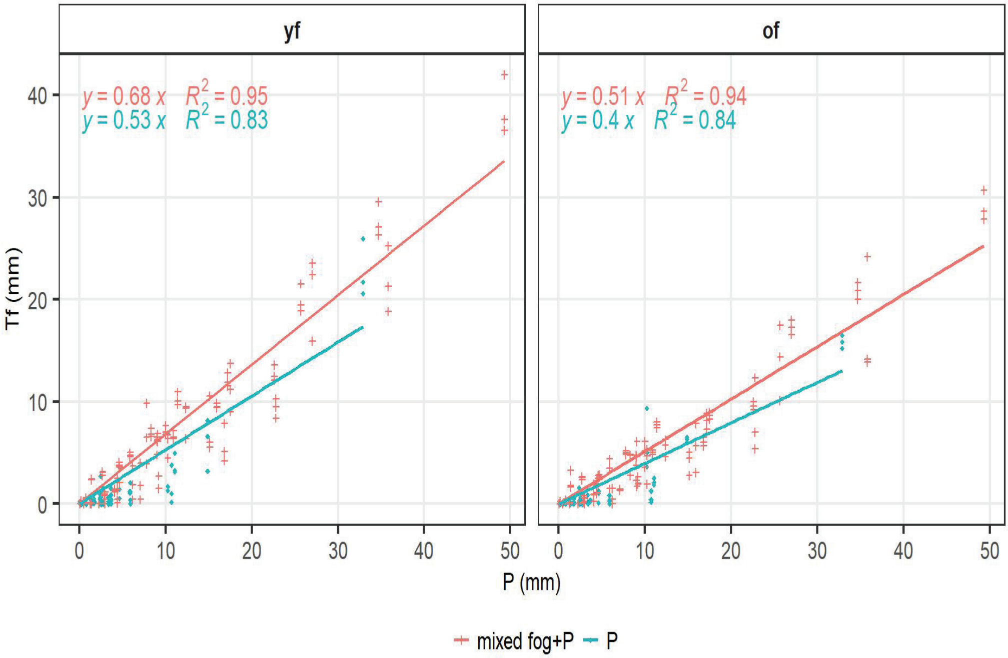
Source: author development.

Measurements of the heights and diameters of the trees were made using manual dendrometers that measures the diameter of a trees. Tree canopies showed interactions with meteorological variables. Such effects were observed in the coniferous forests. The fog contribution to throughfall during rainy days in the young and old forest stand (mean ± standard deviation for absolute amounts) is demonstrated in Table 2. Fog was estimated daily for all single throughfall gauges and negative estimations were set to zero, thus the sum of estimated fog and rain contribution was higher than measured throughfall.

Besides, lichens can also have indirect effect of fog occurrence because fog provides water to these organisms. This can make photosynthesis and develop as a function of water availability. Lichens behave differently in transpiration, because they lose water without high water deficit limitation compared to trees. Such behavior affects the ecosystem response to energy partitioning.

Seasonal hydrological variations in water discharge in the watershed basin demonstrated the following results. River flow outgoing was quantified from 44 ha watershed combining flow velocity and water stage height. The flow velocity was measured at the stream gauge 12 times in the year. The resulting equation describing the correlation between the stage of water (S, cm) and the discharge (D, L s-1) was D=4⋅10-5 S4.504. The correlation coefficient R^2 was 0.991. The resulting river flow showed a pattern with distinct peaks. The prolonged peak was related to snow melting and lasted several weeks in April. In summer, the additional short peaks were observed during intense rains.

Figure 2. Throughfall versus precipitation during mixed precipitation (mixed fog+P) and rain-only (P) events in the young (yf) and old (of) forests

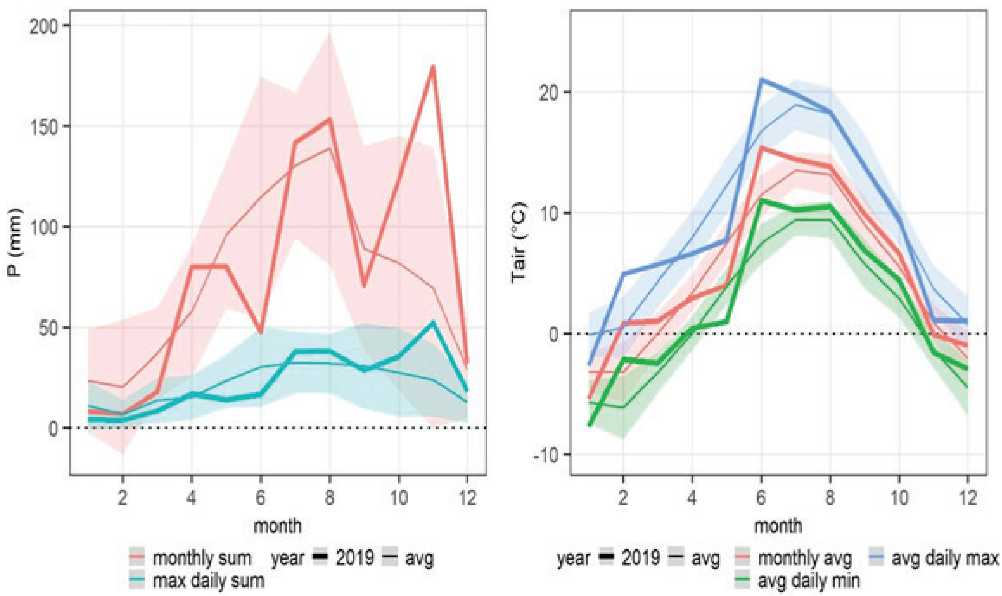


Source: author development.

The response of trees to changes in hydrological patterns were modelled using Python, Figure 2. and Figure 3. The results shown that age, structure, and leaf type of the canopy in the coniferous forest all affect how much water it can absorb, but other elements like mosses and epiphytes can also have a significant impact. As a result, they maintain evapotranspiration, lower the Bowen ratio, raise air humidity, and store water within the forest. In this manner, rain and cloud forests preserve conditions of nearly zero water pressure deficit and provide minimal water stress to leaves, especially to epiphytes. In temperate mountain forests, where needles can survive for years and epiphytes grow on the boles and branches of old trees, this may also be the case.

The average monthly precipitation as a monthly sum and maximum daily sum, showed the importance of convective rainfall events during summer, while the cold winters were comparatively dry (Figure 2). Precipitation was in accordance with 20-year average, except for a drier June and October, and November, which were 1.5 times and more than 3 times wetter than average. This correlation is evident in the maximum daily precipitation. A snowfall event on 8th November, caused a snow break in the young forest. Air temperature deviated from the two-decade average (1999-2019), or February and June were too warm, while May was too cold (Figure 3.).

Figure 3. Average monthly precipitation (monthly sum and maximum daily sum) and temperature (monthly average and average daily maxima and minima) for 2019 (thick line) and for the period from 1999 – 2019.



Source: author development.

Observed data on precipitation showed that in 2019, the amount and seasonal pattern followed the typical pattern, which supported results on the previous 20 years of observation. The total amount of rain and snow, quantified by the pluviometer was above the average (985 mm), while the 20-year average ± standard deviation was 894±187 mm. Exactly 144 precipitations days were recorded, and the maximal daily rainfall was observed during the summer maximum, with 52 mm d-1, Figure 3.

The total annual ET, measured by eddy covariance, was 808 mm. Following the same course as the previous years, the annual ET pattern was skewed, with a maximum in summer. The dominating heat emission can explain this skewness, as it was observed a Bowen ratio above 1 in winter and early spring. This indicated that available energy was used to sustain latent heat and ET in trees only in summer and autumn. Maximal daily ET was in summer (9.4 mm d^{-1}).

The presented findings support the hydrological and vegetation components of the positive feedback loop, which worked especially well in the ancient stand because of its greater ability to retain water in its canopy. This is also noted in an old-growth redwood forest. Besides, epiphytes thrive in environments with consistent humidity. In this study, there are contributed to these goals by presenting modelling of climate and ecological dataset covering South Tyrol.

Conclusion

The results are based on environmental data integration that account for local land development. Specifically, it was demonstrated that forest characteristics were found to be important determinants of hydrological and climate parameters. The results of modelling reported effects of forest age (young or old trees) and specific habitat conditions causing changes in water balance. For example, old trees have a higher water retention capacity, while young forests have lesser water-holding capacity. Besides, trunks and branches are however obviously larger in the old forest sections, but spruce and pine cork have limited capacity to hold water. Besides, presence of fog also affected water balance.

Modelling data is crucial for environmental analysis. Here was analyzed a case study of coniferous forests and hydrology in mountainous areas of South Tyrol. Statistical values of measured environmental parameters were compared and analyzed to reveal temporal trends and quantify the influence of forest trees and climate parameters (moisture and humidity) on habitats. This enabled to detect integrative effects from these factors on ecological sustainability.

Subalpine forests showed the abundant cover of epiphytes, bryophytes and lichens. There was considered species composition and their interaction with the climate to model their water-holding capacity and the effect on the water cycle. Specifically, by combining various measuring techniques, the eco-hydrological balance was evaluated at basin and canopy scales in the Italian Alps. Within the measurement uncertainty range, the difference between water input in the form of rain and snow (excluding fog) and water output as evapotranspiration and water discharge, and variation in soil water content, was 25 mm.

This study supports new data, showing that natural forests are essential for reducing heat extremes over vegetated terrestrial ecosystems. Using modelling and geospatial techniques, it has been analyzed the short and long-term effects of climate-hydrological and environmental factors on land suitability and habitats using datasets across various time periods (1999-2019). Additionally, a descriptive analysis explores the pathways linking habitat sustainability and vegetation health as responses to climate change. The findings reveal that vegetation health is positively influenced by climate and hydrological variations in both the short-term (seasonal dynamics) and long-term periods (two decades). However, decrease of humidity and precipitation has a negative impact, potentially leading to dryness of the vegetation coverage and soil due to the climate change.

For policy makers and local stakeholders, data analysis and modelling present essential sources of information. Thus, Python-based statistical analysis enables to reveal and visualize trends and correlations between climatic and hydrological parameters, and response of vegetation to these processes. This is crucial for understanding of climatic and environmental interactions in natural parks and protected areas. Further research steps can continue environmental observations through data collection, processing and modelling for integrated analysis. For example, enhancing fieldwork campaigns through climate-ecological monitoring supports environmental data analysis and mapping which contribute to environmental protection of precious coniferous forests.

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