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Original scientific paper

Python for environmental modelling of mixed coniferous forests dominated by Norway spruce (*Picea abies* [L.] Karst.) and Swiss stone pine (*Pinus cembra* L.)

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Abstract: Coniferous forests exhibits distinctive ecological and botanical properties that contribute to our understanding of the environmental evolution and dynamics of Earth's landscapes. Their capacity to regulate water balance offers a possible explanation of forest hydrology as essential source of water. This role is expected to become even more crucial under climate change and anthropogenic pressure, respectively. Their various components provide intrinsic mechanism for regulating water cycle and for evapotranspiration partitioning either at the boundary between the ecotones or at the basin level on forested terrain. However, the presence of fog and the role of forest age are challenged due to the potential for high impact factor in eco-hydrological processes. This work applies methods of Python-based data modelling and statistical analysis. Using data modelling, we show experimentally that forest age, height of canopy, daily meteorological factors (fog and humidity) and presence of epiphytes (lichens) have all input on the water balance in the coniferous forests. The meteorological variables were investigated using fieldwork and included evapotranspiration, precipitation, temperature and water pressure deficit. Additionally, the paper proved that fog indirectly contributes to ecosystem water availability because it favours the growth of lichens which influence water cycle through inherent water retention capacity. Technically, this study offers a Python-based modelling of the observed large environmental-climatic dataset at the South Tyrol, Italy. The libraries included Matplotlib, Pandas, and NumPy for data processing and visualization.

Keywords: mountains, conifers, modelling, Python, data analysis.

1. Introduction

Climate-environmental interaction refers to the interplay effect of biotic and abiotic factors on complex ecosystems (Najdovski et al. 2025; Lemenkova, 2022a; Nguyen et al. 2025). Conducting meteorological and hydrological in forest massifs analyses contributes to identifying factors and variables which effects are crucial for environmental conditions of forests and health of trees (Chen et al. 2024). The forests in Alps represent an essential source of water availability in Europe (Karinou et al. 2025). This a role is even more crucial under the conditions of climate change (Khaine and Woo, 2014; Stevens et al. 2021). Coniferous vegetation interacts profoundly with the water cycle, influencing both water availability for human needs and the distribution between sensible and latent heat. Therefore, it interacts with the radiative forcing feedback mechanisms (Goude et al. 2022). Forests are well known as a reservoir for regional hydrology and inferred to contribute to the hydrogeological resources observed in regional level. Nevertheless, despite the crucial role of forests in hydrological regulations, few studies investigated the functionality of mountain ecosystems in subalpine belt of Europe.

Although holding promising applications in precision environmental modelling, silviculture studies require larger sample sizes than regular tests at catchment level for identifying marginal effects from lichens, fog and other eco-hydrological parameters (Scholl et al. 2011). These factors greatly limits potential correlations between climate and health of forest stands in Alps. Recent studies underscore the role of the Alps as a principal European watershed, supplying water to extensive lowland areas (Lemperiere and Marage, 2010; Schumacher and Bugmann, 2006). In the Alps and other Central European mountains, the subalpine elevation belt is mostly covered by forests dominated by conifers. Over the past decade, the emergence of environmental monitoring of coniferous forests has motivated a rapid growth of modelling and computing techniques that are associated with advanced climatic-environmental studies (Klaučo et al. 2017; Lemenkova, 2024a, 2024b). The examples include the use of machine learning for forest monitoring (Pimenow et al. 2025), the use of remote sensing data for environmental mapping, high-level computational techniques for big data processing covering large massifs of forests.

Most of these analytical approaches are designed for quantitative modelling of the environment and climate parameters of land cover types (Mandl et al. 2023; Lemenkova, 2025b; Bakker and Veldkamp, 2008). Hence, they are only applicable to a restricted study areas at landscape and patch level. Statistical testing of meteorological data on climate parameters in medium-size coniferous forests require fitting full models across the sample size in watershed level. Thus, such studies are computationally intensive when applied to a large-scale smaller test areas. To improve the accuracy of land management, scalable methods such as artificial intelligence (Cho and Ackom, 2025; Lemenkova, 2024c; Xiao and Xiao, 2025) and deep learning (Troles et al. 2024; Lemenkova, 2024d) have been proposed in many studies on silviculture, environmental monitoring and sustainable development. Applications of such advanced methods for forest mapping and monitoring aims at developing effective framework for land management of protected national parks and ecologically restricted areas (Bird et al. 2000; Klaučo et al. 2013).

1.1. Objectives and goals

As an extension of many programming methods, Python or R statistical approaches to data processing are developed for quantitative trait analysis of environmental datasets in large volumes (Dilaver et al. 2025; Lemenkova, 2019, 2025a; Barreau, 2025). This is especially actual for climate-environmental observations in forests. For instance, using Eddy covariance technique implies taking measurements every 30 minutes during several years. Such intensive data observations result in big volume of data which requires advanced methods of their processing. In contrast, using rapid and accurate methods of numerical data handling by Python programming language provides more efficient approach to data analysis (Luo and Xu, 2019).

In this study, we present the use of Python-based modelling for analysis of diverse climate and environmental parameters in coniferous forests of the Tyrolean Alps. The techniques of statistical analysis are applied for environmental analytics following previous research examples (Newton, 2018; Lemenkova, 2023). The main objective of this study is to analyze the role of forest in water balance with regard to age of trees: young stands (<30 years old) and old stands (> 200 years old). Specifically, the study investigated partitioning of precipitation between water intercepted by the canopy and the soil and water discharge of mixed forests of fir, spruce and pine on subalpine mountains, in permanent sample plots.

Python libraries (version 3.13.3) of statistical analysis were applied to analyze datasets using modelling techniques. First, we investigated what is the average fraction of water intercepted by vegetation in coniferous forests. Second, in the context of the interaction of forests and meteorological drivers, we analysed the conditions of climatic change for a better understanding of the ecohydrology of a subalpine forested catchment. To this end, the following goals were target: modelling revealed the direct contribution of fog to water input and the fraction of water transpired by the vegetation. Besides, using Python tools, we detected differences between old and young forest formations in the water interception capacity and found that older trees are more capable in water interception. Finally, the role of epiphytes with a case of lichens also played the role through distribution on trunks.

2. Material and methods

The experiment was conducted in the Italian Alps (1735 m a.s.l., 46°35′11″N, 11°26′00″E) (Figure 1). The catchment has an area of 0.44 km^2. At the site, it is present a 40 m tall tower where eddy covariance measurements are routinely performed giving the data on evapotranspiration at a half-hour time step. The water basin where the experiment was conducted was mapped in GIS software. The data included the Shuttle Radar Topography Mission (SRTM) which provided a Digital Elevation Model (DEM) for a detailed representation of Earth's terrain.

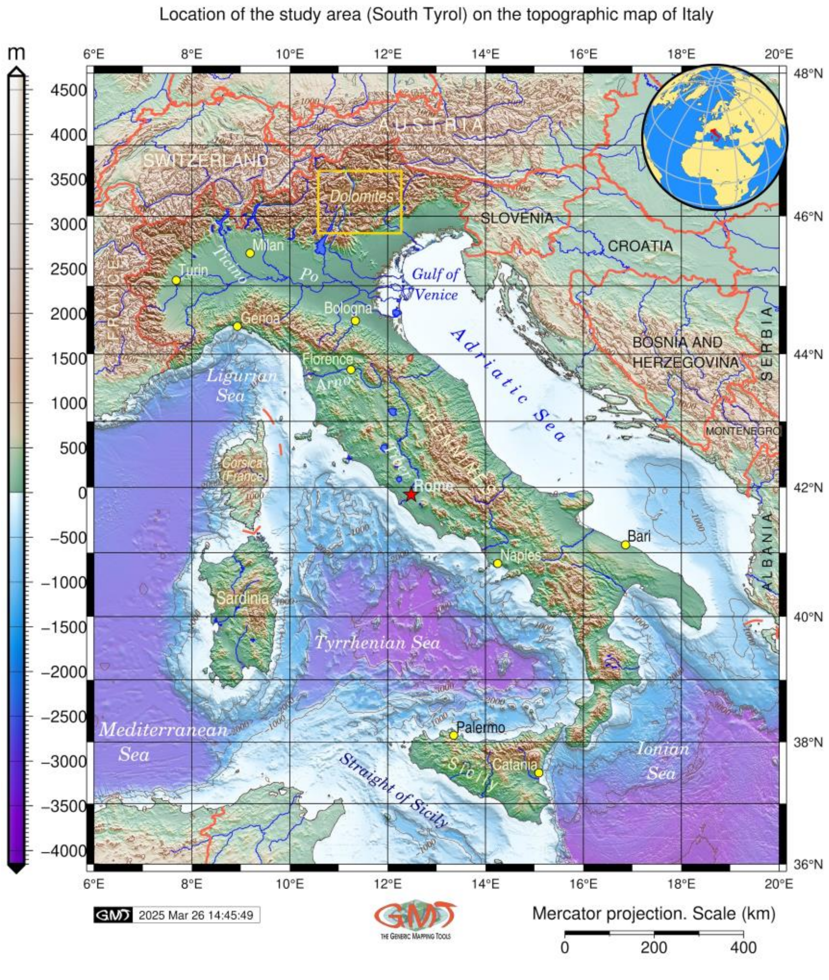

Figure 1. Study area (yellow square) on the topographic map of Italy. Map source: author. Software used: Generic Mapping Tools (GMT), version 6.5.0. Data: GEBCO raster grid.

Subalpine forests play a crucial role in partitioning precipitation inputs, with canopy interception processes determining the proportion of water that reaches the soil or is lost as evaporation. In this area, the soil has developed above a layer of glacial till, with a depth of ca. 1 m, placed on top of a porphyry bedrock. The soil was classified as Haplic Podzol according to the FAO soil taxonomy. On average, it consisted of 49% sand, 39% silt, and 12% clay. The forests are characterized by structural diversity, i.e. a series of transitions from diverse to complex selection with diverse structural forms of trees. 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 mean tree height was approximately 29 m.

The understory consisted mainly of blueberry (*Vaccinium myrtillus* L.). Intervening grasslands were dominated by wavy hair-grass [*Deschampsia flexuosa* (L.) Trin]. Due to the limited dataset, the hydrogeological measurements are expected at the catchment level and show the contribution of fog water to the hydrological cycle in forests. These restrictions could serve as the principal factor for limitation of modelling using elements of ecosystem in the coniferous forests of north Italy.

Mountain forests have a specific combination of temperature and precipitation. 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 were arranged in rows between each pluviometer and data were recorded on a weekly basis. In some cases, the combination of high precipitation and low temperature is unique, exceeding the combination of transpiration (T) and precipitation (P). Tree transpiration was calculated by dividing sap flow by the projected crown area of the respective tree, thereby converting units from kg per tree to mm. The crown area was estimated from the mean radius in four directions. The average tree transpiration of the two smaller ones was used to represent the young stand, while the average of the three larger trees was used to represent the old stand.

Partitioning of evapotranspiration (ET) into evaporation from the soil and transpiration of canopies (T) is important task to assess biomass production of forest and the allocation of water resources. Here, evapotranspiration partitioning was evaluated using tree transpiration which was estimated by measuring the sap flow of five spruce trees. The sap flow measurements showed a representative behaviour of these trees for their size classes. One sensor of the tissue heat balance was installed on the trees. The measuring system provided sap flow rates integrated for the whole sapwood depth per unit trunk circumference. The measured values were logged at regular intervals and then scaled to the tree level by multiplying with stem circumference and integrated for each tree. After data collection and processing, the plotting of figures showing visualization of the models is done using Python libraries.

When it comes to wood production, the characteristics of trees are is a crucial factor that encompasses more than botanical parameters. The forest is of natural origin and managed traditional harvest method using gaps, ca. 50 m wide, that involve the thinning of surrounding trees. Functionality of such method is now an integral part of the wood production process. It is essential to create an optimized method of wood monitoring and production that offers a distinct and standardized experience. One of the primary hurdles is to create heterogeneous vegetation structure, with groups that are almost even-aged and form an aged structure with different ages at a larger scale. The arrangement of study site resulted in a group of investigated trees, including a large group of dominant spruce trees with an age of approximately 200 years, and a second group of young, about 30 years-old trees were present at the study site. Such heterogeneity is necessary for statistical analysis.

The role of lichens in the water balance was assessed by measuring air temperature and humidity inside the crown. Besides, water storage capacity of the lichens was evaluated at two different tree heights. The water storage capacity of the lichens was assessed in spring from a tree falling in the previous winter for the old stands. To estimate the lichen weight, the tree was divided into sections. In each section, all the branches were counted, and all lichens present above a randomly selected branch were collected, together with the lichens growing on half of the main stem. In the laboratory, the lichens were first wetted until water saturation and then weighed to assess the fresh weight. They were then dried in an oven until a constant weight was achieved and then weighed to assess their dry weight.

Evapotranspiration was assessed by the eddy covariance. The instruments were placed on a tower at over 30 m above ground. Air samples were taken through an insulated steel tube. Raw values of CO_2 and H_2O concentration and 3D wind speed components were measured at 20 Hz and the resulting fluxes were computed and logged by a personal computer every 30 min. and elaborated with Eddypro. Additionally, water discharge at the catchment scale was measured by a combination of a water stage sensor and flow velocity tests using salt dilution.

The role and contribution of fog were estimated by its impact on throughfall. Fog and fog mixed with precipitation might directly reduce transpiration rates by creating a cooler, more humid microclimate that limits water loss from vegetation. First, a linear regression equation was determined between throughfall and precipitation rates for mixed precipitation and rain-only events for both stands. These gave a predicted throughfall for a given precipitation event with rain only and with fog (mixed precipitation). Afterwards, fog contribution to throughfall for mixed precipitation days was estimated as the difference between measured throughfall and the contribution of rain to throughfall calculated as the sum of precipitation and the slope of the throughfall to precipitation equation from rainy days. The precipitation in the forest was evaluated by a weighing pluviometer and the dataset converted to tabular format for Python-based processing.

3. Results and discussion

The expanding scale and complexity of the environmental modelling using climate-meteorological datasets require accelerated analytical workflows. Python meets this need through an adaptive framework enhanced for high-speed and accurate analysis. This study provides novel insights into the water balance components in temperate subalpine forests using Python. In this way, it offers crucial advancements in ecohydrology and enhancing the accuracy of water balance models vital for understanding climate-forest feedback mechanisms in coniferous stands of different age. At the core of the statistical packages of Python, the algorithms of data analysis dynamically generate optimized central processing units and graphics processing units code variations, which enabled us to perform graphical modelling and environmental learning from the dataset.

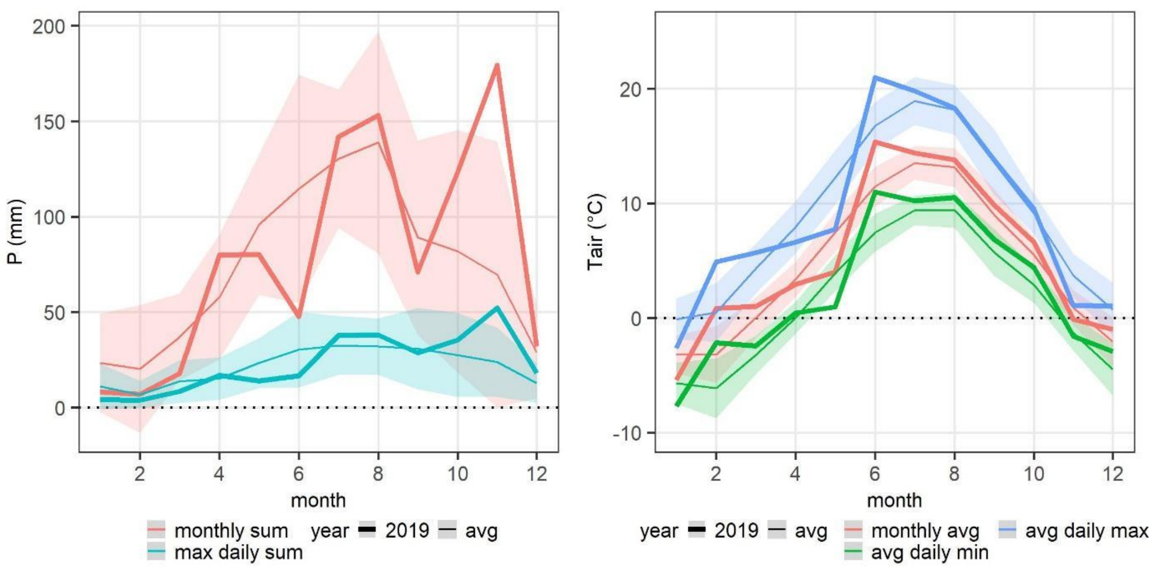

Figure 2. Average monthly precipitation and temperature.

The results of the research indicate that during the analyzed period the hydrology of mixed forests of spruce and pine have undergone a number of changes in key elements: precipitation, evapotranspiration, temperature and water pressure deficit. Transpiration accounts for approximately 60-80% of the total evapotranspiration in inner alpine pine forests during the growing season. This highlights the critical role of vegetation transpiration in the water balance of subalpine forests in water-limited environments. The variability was related to forest age (>200 y.o. and <30 y.o.) and structural environmental features (Figure 2). The significant presence of trees with canopies of large dimensions accelerated the humidity and favored water accumulation according to the dynamics of stands. Moreover, presence of lichens had a positive impact on water balance development and, in general, on the of these stands to water interception. In forest ecosystems, interception is influenced by canopy structure, density, and the prevalence of epiphytes, which can substantially affect how much water is retained versus discharged. Interception in dense subalpine forests can account for a significant fraction of precipitation, with studies showing up to 35% of rainfall intercepted in certain alpine coniferous forests. The meteorological data was modelled according to monthly sum and maximum daily sum, as well as monthly average and average daily max and min for 2019 (thick line) and for the period from archive datasets (1999 – 2019) (Figure 2).

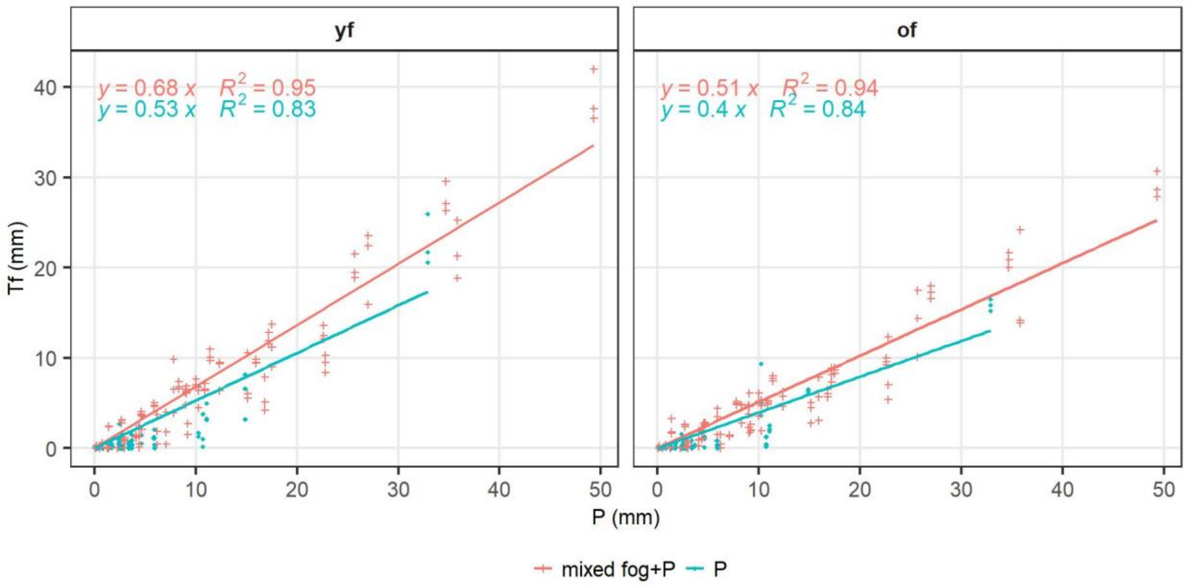

Figure 3. Correlation between throughfall and precipitation for young (yf) and old (of) forest.

Python-based data analysis presents is a scalable and accurate method to analyze environmental datasets. In this regards, data processed from highly instrumented long-term monitoring site were evaluated and the variation at several depths and tree trunks (with different canopy and age) were investigated (Figure 3). Additional measurements included water discharge, sap flow, throughfall, fog interception and water holding capacity of lichens. The Italian subalpine forests show an abundant cover of epiphytes, bryophytes and particularly lichens. In this study we assessed their species composition and their interaction with the climate. Specifically, we highlighted the correlations between variables (temperature, evapotranspiration, precipitation) predicting the fastest based on input data and output graphical results. This data-driven optimization of scripting libraries aimed at climate-environmental analysis achieves considerably faster processing comparing to other tools for data analysis (Elkin et al. 2015; Lemenkova, 2021). As a result, using Python for modelling forest eco-hydrological datasets becoming broadly relevant computing fields requiring efficiency, such as environmental analysis (Figure 4).

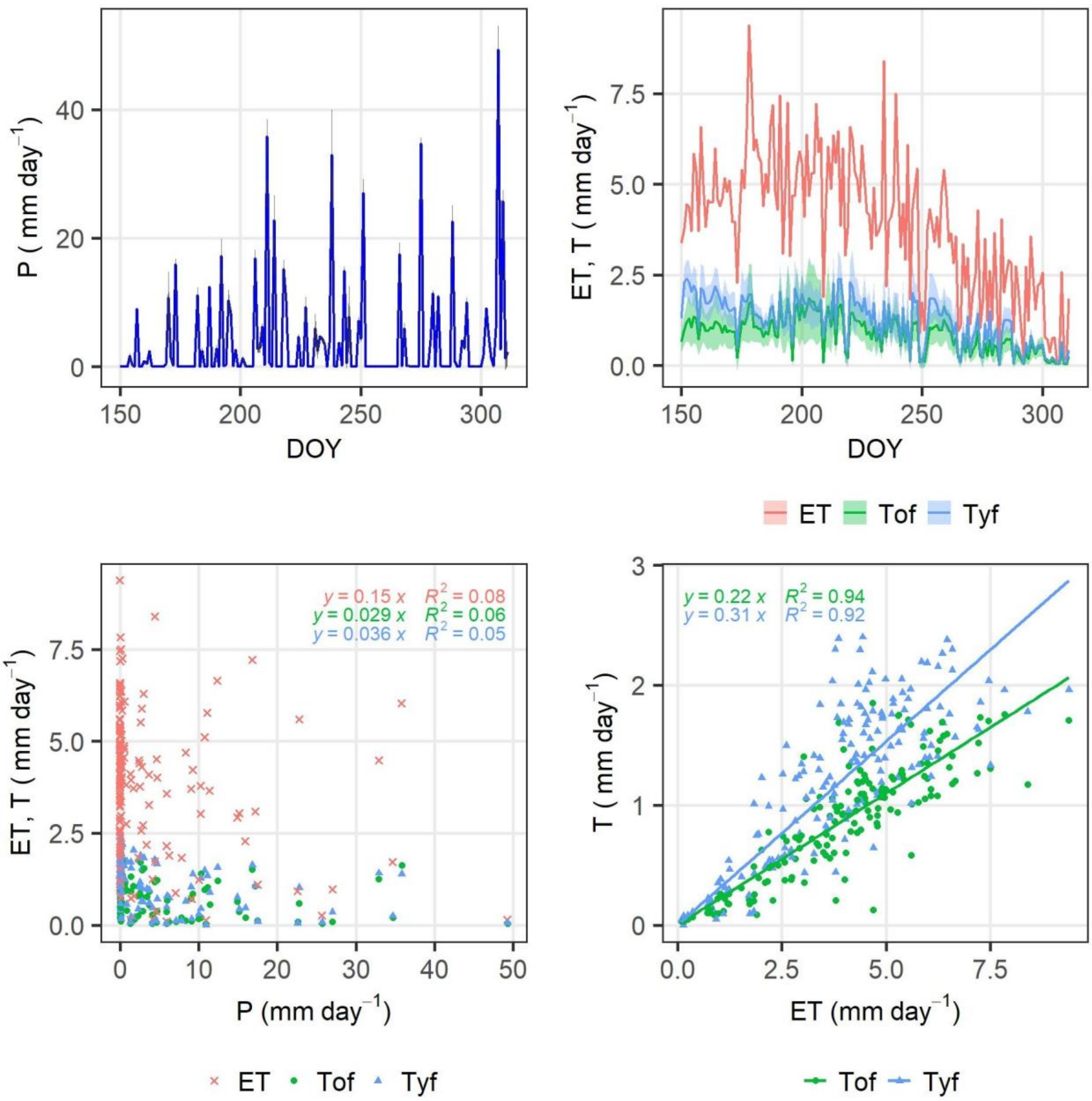

Figure 4. Precipitation (P), evapotranspiration (ET) and transpiration (T) for old and young forest. The abbreviations Tyf and Tof are related to the transpiration recorded in the stands of young and old forests.

Here, we observed several differences in the ecosystem water partitioning at the catchment level for the measuring period, between the young and old stand. Throughfall and transpiration were higher in the young forest. Consequently, interception which was calculated as the residual of total P minus Tf minus Sf was lower in the young stand. As intercepted water eventually evaporates back to the atmosphere, interception accounted for a major part of ET (54% in the old forest and 33% in the young forest). Evaporation is a part of the water cycle and provides a shortcut for precipitation water to return to the atmosphere without having to pass through the soil or the living parts of plants. This partially explains the low transpiration/ET ratios. The evapotranspiration of soil and understory was calculated as the residual of ET (Eddy covariance) - T - I, and was higher in the young stand, where the interception was much lower.

The demonstrated Python-based modelling ensures the significance of rainfall and fog interactions through visualised relationship of throughfall and precipitation, and underscores the impact of upstream forest management on water availability during critical dry periods. This is useful information for downstream stakeholders reliant on stable water resources. Figure 5 shows statistical diagrams on evaluation of the meteorological parameters (ratio of diffuse to total global radiation, VPD, and relative air humidity (RH) during periods with fog.

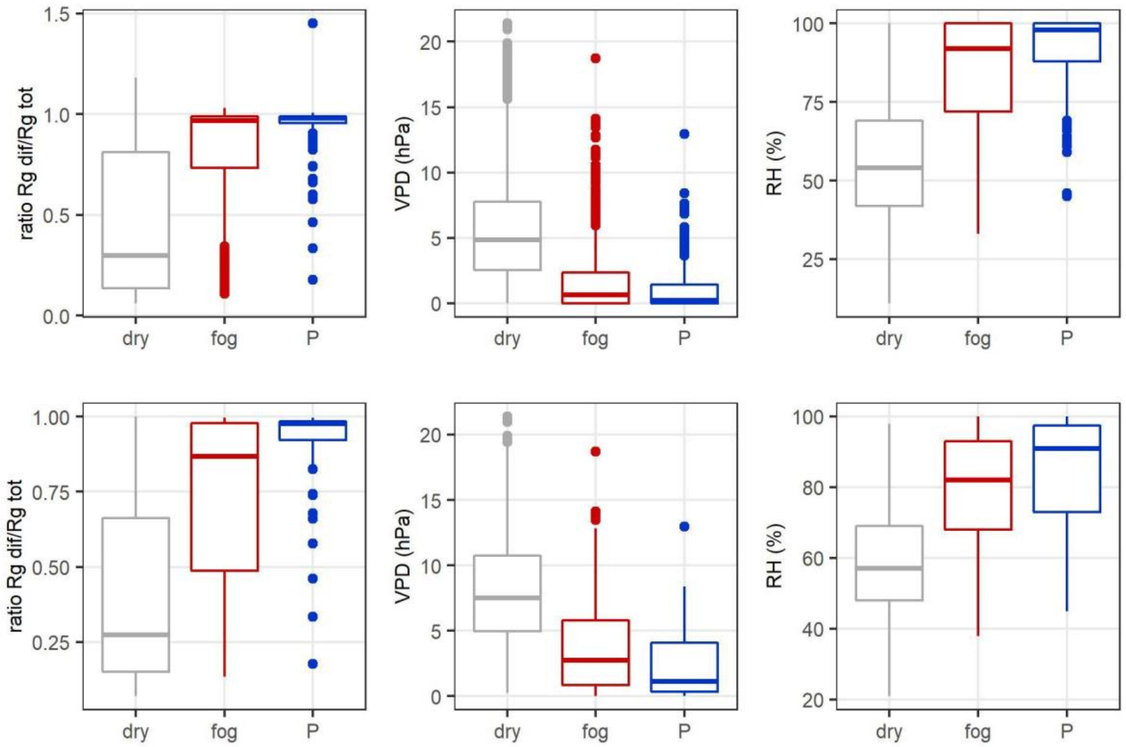

Figure 5. Meteorological parameters (ratio of radiation Rg, water pressure deficit VPD, and relative air humidity (RH).

The discharge (DC) and the change in soil water content (dSWC) completed the water balance as both were measured for the entire forest, the same values were used for both forest types (young and old). Both DC and dSWC were of minor importance compared to T. Most of the discharge occurred during snowmelt in spring before the start of the measurement period. Changes in soil moisture are important in water balance computation only at short time scales and had nearly levelled out over the entire measuring period.

By elucidating the roles of canopy structure and epiphytic communities, the findings achieved by Python support conservation strategies aimed at preserving water-retentive forest features. In this way, it enhances resilience to climate variability. Specifically, models confirm the positive feedback between hydrological and vegetation components, which were effective in the old stand due to its higher capacity to store water in its canopy. This was also observed in an old-growth redwood forest. In addition, epiphytes survive in humid conditions, therefore, fog link the positive feedback loop between the presence of lichens in old-growth forests and cool and humid meteorological conditions.

Additionally, the results have direct applications for policymakers in environmental modelling (Newton, 2012). Considering the results, it is possible to emphasize the importance of old forest conservation (trees of >200 y.o.) as a natural buffer for watershed protection and climate regulation. Environmental monitoring is necessary for forest management which is based on ecological principles. Protecting forests from clear cutting as much as possible and assessing ecological importance of trees for water balance is essential for land management and green economy. A specialized form of environmental data modelling is the selection of software approaches which relies on data structures and volumes in mixed-species coniferous forests and on the climate local conditions of individual dominant trees. In this study, we applied Python for environmental modelling and demonstrated its effectiveness for graphical modelling and visualization of the correlations between diverse hydrological, climate and ecological variables (humidity, radiation, water pressure deficit, evapotranspiration, temperature and precipitation).

The study is represented by the coniferous mixed forests dominated by Norway spruce (*Picea abies* [L.] Karst.) and Swiss stone pine (*Pinus cembra* L.). Norway spruce (*Picea abies* [L.] Karst.) is a precious species of spruce native to Northern, Central and Eastern Europe (Hasanagić et al. 2025; Nechita et al. 2025). Besides ecological significance, Norway spruce (*Picea abies* [L.] Karst,) has a wide distribution of its commercial values as a source of wood, and is also the main Christmas tree in multiple countries worldwide. Swiss stone pine (*Pinus cembra* L.) is important species for silviculture, because it has unique characteristics that enable it to adapt to the upper altitudinal limits of forests and maintain growth in challenging environmental conditions (Budeanu et al. 2025; Alperth et al. 2023; Izworska et al. 2023). At the same time, Swiss pine (*Pinus cembra* L.) is one of the conifer species that has high contents in active phytochemicals which is valuable for medical purposes (Coman et al. 2023). Nevertheless, this species is not sufficiently studied in spite of its ecological importance. In this regard, the great potential would be integrated environmental-climatic analysis supported by advanced tools of Python programming for analysis of forest stands and environmental monitoring of precious coniferous forests.

4. Conclusions

Cumulatively, Python libraries of the statistical data analysis deliver adaptive performance optimization while processing data. This enabled to accelerate data analysis and modelling while retaining several variables (evapotranspiration, temperature, precipitation, and age of forest of old > 200 y.o. and young < 30 y.o. trees). Such flexible framework is important and accurate, given the expanding volumes of environmental data and the need for data-driven reactive analysis for forest conservation and landscape protection in silviculture domains. The optimization principles of data analysis embodied in Python's libraries can be extended to other scientific workloads with similar datasets requiring high computational efficiency. As data scales expand, Python offers researchers an actively improving platform to execute demanding workflows in environmental analysis in forest stands. We conclude that environmental and climatic factors have been stable in mountainous forests since the formation of ecosystems.

In this study, it was shown that environmental-climate variables (precipitation, temperature, evapotranspiration) and hydrological parameters (radiation, VPD, and relative air humidity) are important traits with significant roles in forest growth, development, and overall protection in silviculture. Here, we employed a straightforward Python algorithm of data processing to estimate these traits in different parameters mentioned above. The variables were estimated for old (>200 y.o.) and young (< 30 y.o.) forest stands. Functioning within a Python environment, the algorithms of statistical data analysis are independent for any operation system (Mac, Window, Linux) and does not necessitate additional software for analysis. This creates clear advantages of scripting in environmental silviculture domain, besides the console-based approaches (Liu et al. 2023; Lemenkova, 2022b). Incorporation of the in-situ fieldwork, and statistical modelling methods in the framework of data processing supports the process of data analysis, eliminating the need for additional intervention.

The statistical methods of data analysis by Python are used to determine the correlations between the analysed values by standardizing the trends and dynamic range of the graphs (e.g., relationships between the radiation, VPD, and relative air humidity, etc for young and old forests). In addition, the algorithms automate the data modelling process based on mathematical foundations until a graphical visualization is obtained. Other methods that can be recommended for future consideration include, for instance, artificial intelligence, convolution neural network (Raman and Jayaraman, 2025) and deep learning procedures. Such and similar approaches might pose challenges for silviculture researchers through facilitating data analysis for forest protection and monitoring using advanced statistical and programming algorithms of Python.

The programming libraries of Python are adaptable, allowing environmentalists to modify them according to specific datasets that were obtained using Eddy covariance or other toolsets. Hence, the data analysis does not demand additional advanced computer devices which creates valuable advantage of Python. Furthermore, the algorithms of Python calculate connected components of the environmental and climate variables, enabling users to set thresholds for dependence between the variables in several dimensions (e.g., evaporation for young and old forests with regard to temperature and external precipitation). To conclude, this study contributed to development of the advanced methods of data processing in silviculture with the case study of coniferous forests dominated by Norway spruce (*Picea abies* [L.] Karst.) and Swiss stone pine (*Pinus cembra* L.).

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