Biophysical climate mitigation potential of coniferous forests in temperate ecosystems of South Tyrol

Potentiel biophysique d'atténuation du changement climatique des forêts de conifères dans les écosystèmes tempérés du Tyrol du Sud

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Vol. 35.2 / 2025, 22-38

GEOREVIEW

Received:
24 March 2025

Accepted:
25 June 2025

Published online:
8 July 2025

How to cite this article:
Lemenkova, P. (2025) Biophysical climate mitigation potential of coniferous forests in temperate ecosystems of South Tyrol. Georeview, 35, 2, https://doi.org/10.4316/GEOREVIEW.2025.02.02

ABSTRACT: Forests affect climate parameters through impacts from biochemical and biophysical processes. However, the effects of the coniferous stands on hydrological setting in temperate regions have received little attention. This study investigated impacts of forest with different ages on water balance. The dominated species include spruce (*Picea abies L.*), Swiss stone pine (*Pinus cembra L.*) and Scots pine (*Pinus sylvestris L.*). During fieldwork campaign, data were collected on temperature, radiance, precipitation, evapotranspiration, throughfall, humidity and vapour pressure deficit. Data modelling reveals the relationship between the characteristics of forests (tree age, height and canopy structure) and meteorological parameters on water balance. This study supports silviculture, forest management and sustainability of Alpine environment in North Italy.

KEY WORDS: environment, monitoring, radiance, meteorology, ecology.

RÉSUMÉ : Les forêts influencent les paramètres climatiques par l'impact des processus biochimiques et biophysiques. Cependant, les effets des peuplements de conifères sur le cadre hydrologique dans les régions tempérées ont reçu peu d'attention. Cette étude a examiné les impacts de forêts d'âges différents sur le bilan hydrique. Les espèces dominantes sont l'épicéa (*Picea abies L*), le pin cembro (*Pinus cembra L.*) et le pin sylvestre (*Pinus sylvestris L.*). Au cours de la campagne de terrain, des données ont été collectées sur la température, l'ensoleillement, les précipitations, l'évapotranspiration, le pluviométrie, l'humidité et le déficit de pression de vapeur. La modélisation des données révèle la relation entre les caractéristiques des forêts (âge des arbres, hauteur et structure de la canopée) et les paramètres météorologiques sur le bilan hydrique. Cette étude soutient la sylviculture, la gestion forestière et la durabilité de l'environnement alpin dans le nord de l'Italie.

MOTS CLÉS : environnement, suivi, rayonnement, météorologie, écologie.

1. Introduction

This study presents the multi-disciplinary analysis of the coniferous forests in the Italian Alps. The aim is to reveal the effects of water balance and hydrological parameters on vegetation in the coniferous forests. Specifically, we produced a spatially explicit assessment of links between vegetation (coniferous trees) and hydrological balance. To evaluate effects of the meteorological characteristics (average air temperature (T), air relative humidity (RH), and vapor pressure deficit (VPD) on forest stands, we performed a statistical data analysis using dataset obtained from the fieldwork in the mountainous areas of the protected Italian Alps. To do so, the generalized dissimilarity modelling was performed using Python to evaluate the function of climate setting on ecological parameters (canopy height, presence of lichens on tree trunks and age of forest stands) by remote sensing approaches (Eddy covariance flux measurements and hydrological data collection). The comparison of old and young forest stands allowed to highlight areas of forests where effects from external factors (presence of lichens and repeatability of fog) affected the eco-hydrology.

The research on how forest can locally transform climate setting towards a more sustainable hydrological cycle has become a growing priority in environmental sciences and land management (Klaučo et al., 2017; Zhang et al., 2024). Nevertheless, the task of generating actionable knowledge and advising silviculture authorities on the ongoing processes in the mountainous forests remains profoundly challenging (Antoniadis et al., 2024; Lemenkova, 2025a; Yin et al., 2007). This is partly due to the complex nature of the water balance and the interaction between its components, where ecological and meteorological processes interact in dynamic way. Besides, meteorological and environmental data should be treated using advanced modelling tools for accurate analysis (Klaučo et al., 2013; Lemenkova 2025b; Wei et al., 2004). The discussion on the role of forests involves debates about silviculture needs and ecological restoration of forest stands. Identifying a problem of water balance is far simpler than formulating and implementing research questions based on the meteorological datasets (Yang et al., 2024).

Mountain regions are of essential importance for water provision with an impact extending far wider than their actual range. The Alps represent an essential source of water availability in Europe, a role expected to become even more crucial under climate change conditions (Štraus et al., 2023). Vegetation interacts profoundly with the water cycle, influencing both water availability for ecosystems and the distribution between sensible heat and latent heat, therefore interacting with the radiative forcing feedback mechanism. Environmental systems are substantially affected by natural and human disturbances and include different components that form ecosystems: topography, climate setting, vegetation coverage, soil types, landscapes (Du et al., 2025; Li et al., 2025; Lemenkova, 2022a, 2022b; Habeeb and Mustafa, 2025). However, related biophysical feedback to climate and water balance is not yet well analysed. This study aims to model the biophysical impact of changes in forest age, height of canopy and presence of lichens on land surface temperature. Using Python-based modelling techniques, we illustrate the mechanisms underlying temperature differences in coniferous forest stands with various characteristics.

The relevance of fog for the water balance of temperate mountains of Alps is still unknown. Previous studies suggested that the alpine contribution of fog is limited, besides the frequent occurrence of low-elevation clouds. A distinct feature of alpine fog, as compared to fog occurring on islands, and promoting the occurrence of fog vegetation, is that fog frequently occurs together with liquid precipitation, determining the ‘mixed precipitation’ events.

Another topic relevant to the understanding of subalpine forest ecohydrology is the evapotranspiration (ET) partitioning between evaporation (E) and transpiration (T). Recently, several models have been developed to partition ET and these models have been tested across several climates, plant functional types and sites. Alpine forests, however, have their specificity. First, considering that the soil is covered by high vegetation with dense foliage, we can assume that soil evaporation represents a minor source of E as compared to wet canopy E, contrary to what happens, for instance, in sparse broadleaved forests like woody savanna. Secondly, Mountain forests have a specific combination of temperature and precipitation. In some cases, the combination of high precipitation and low temperature is unique, exceeding the combination of T and P. The site with the highest degree of water intercepted by the canopy, therefore promoting a large fraction of wet canopy E. In this way, current paper contributes to a better understanding of hydrological-climate relationships. This paper contributes to the development of effective silviculture in European Alps. Further applications of this study can be extended on plant biodiversity and ecosystem change in the Italian Alps and in particular, the climate effects in the protected areas of Alps. In this way, this study presents an approach integrating fieldwork observation and data collection, statistical data analysis, and investigation of meteorological and biophysical variables for climate-environmental analysis.

2. Study area

This study was conducted in a coniferous forest ecosystem of the South Tyrol, north Italy (46°35′11′′N, 11°26′00′′E), located in subalpine environment, Figure 1. In this region, many areas of forests underwent a process of spontaneous restoration due to the positive and profound effects of the forest protection. Nevertheless, the ecological consequences of climate effects on forests comparison of young and olde trees are still to be fully understood. These areas can therefore be seen as a representative quasi-experimental benchmark for assessing how active forest conservation positively performs in tackling biodiversity loss in coniferous forests and improves the resilience of natural ecosystems to climate change.

The study area is located in the mountain range in north-eastern Italy and represents the southeastern outpost of the Alpine Dolomites. It extends for about 70 km and is considered one of the best coniferous areas in the Dolomites. Through traditional agro-pastoral activities are still taking place, mainly in the sub-mountain belt, these decreased substantially in the last three decades. Most of the area is protected as the natural reserve area. The mean elevation of the study area from the mean sea level is 1735 m a.s.l. This area is characterized by a temperate climate, however, it features the effects of the humid subtropical climate with hot summers and very cold winters compared to other Italian regions. Located at multiple climate borders, this region includes vegetation of various types. However, the dominating species in the specific study area are coniferous. The undertaken measurements are collected in the coniferous forests of South Tyrolean Alps in foggy and non-foggy days. In the Alps and other Central European mountains, the subalpine elevation belt is covered by forests dominated by conifers, Figure 2.

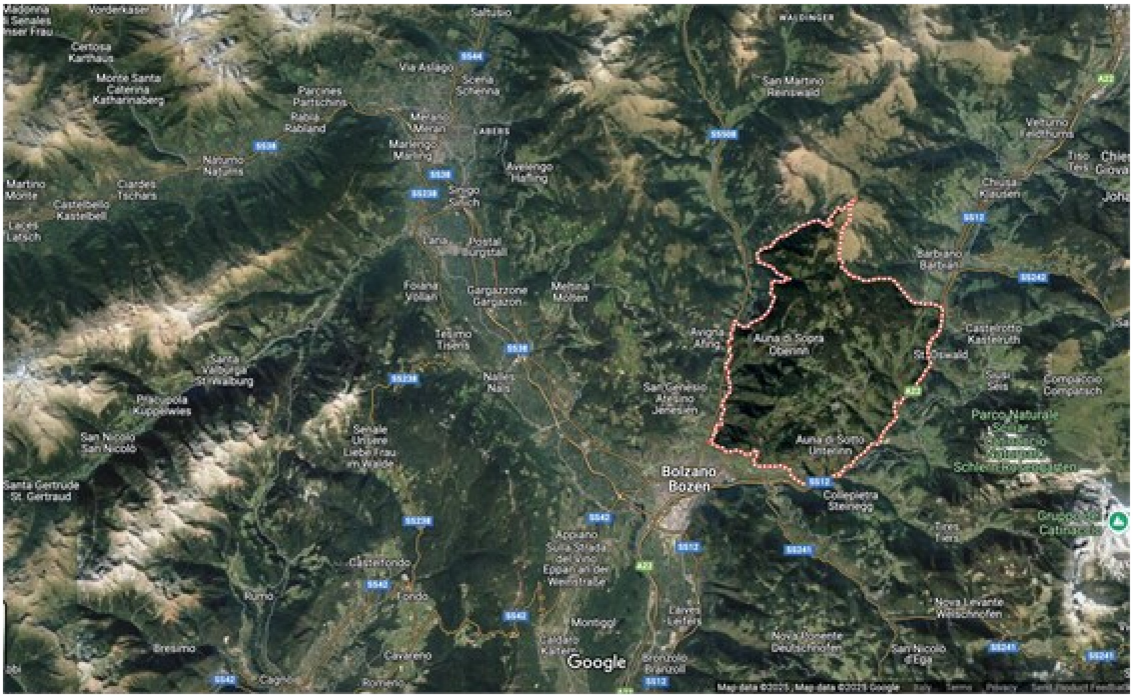

Figure 1 Location of the study area. Source: Google Earth aerial imagery, 2025.

Figure 2 Measurements in the study area.

The eastern part of the Alps is particularly humid and is dominated by spruce forests. In South Tyrol, spruce forests cover 178,000 ha: 52.8% of all the forests in the region, which is covered by forests on 45.7% of its surface. The evaluated parameters included the establishment, growth and health of coniferous forest with dominated composition of spruce (*Picea abies L*), sparce woodlands of Swiss stone pine (*Pinus cembra L.*) and Scots pine (*Pinus sylvestris L.*), Figure 2. Additionally, other species include *Fagus sylvatica* forests with large locally dominated by Abies alba. Moreover, *Larix decidua* is often presented at lower elevations, *Carex curvula* grasslands and *Salix herbacea.* The beds and heaths of *Rhododendron ferrugineum* and *Vaccinum spp.* dominate at higher elevations. This area is under natural protection initiative and presents the natural and environmental heritage of Italy. On the mountain slopes, the dominant land cover types include croplands and pastures in local mountain settlements. Generally, the orographic structure of this region is characterized by the elevation range from ca. 1000 to 2000 m. a.s.l. which was partially determined by quaternary glaciations in the past. This complexity offers a wide range of microclimate conditions, resulting in very high plant and habitat diversity of Dolomites. Thus, this region hosts more than 650 species among which rare exemplars. Considering forest age in such environmentally precious regions facilitates forest management and supports local climate mitigation and adaptation in future climate change, environmental monitoring and sylviculture.

Subalpine forests often show the abundant cover of epiphytes, bryophytes and lichens. Previous studies assessed their species composition and their interaction with the climate (Liu et al., 2023; Ji et al., 2024). However, little is known about their water-holding capacity and hence the extent of their interaction with the water cycle. Due to their poikilohydric nature, they are also expected to behave differently in terms of transpiration, losing water without high water deficit limitation as the trees do. This behaviour affects the ecosystem's response to energy partitioning. From a forest management perspective, this study seeks to understand whether young or old forests, growing in this habitat, have a higher water retention capacity. For instance, trunks and branches are larger in the old forest sections, but spruce and pine cork have limited capacity to hold water.

3. Objectives and goals

In this study, we perform the computational research aimed at developing ecological modelling using several components: forest stands of different ages (old>200 years and young<30 years), meteorological data such as precipitation (P), temperature (T), evapotranspiration (ET), and water pressure deficit (WPD), and actionable knowledge for transformative change of forest landscapes. Additionally, the presence of lichens and fog occurrence can also present an indirect effect on water balance. Fog is extremely effective in providing water to these organisms, which can make photosynthesis and develop as a direct function of their water status. Therefore, we try to consider several environmental components to answer the following questions:

i) What is the average fraction of water intercepted by vegetation?
ii) What is the direct contribution of fog to water input?
iii) What is the fraction of water transpired by the vegetation?
iv) It there difference between old and young forest for water interception?
v) What is the role of epiphytes in the canopy water retention capacity?
vi) How the contribution of forest of different ages (young < 30 years old, and old > 200 years old) differ in for water balance.
vii) How fog react in local microclimate and what is the role of fog in eco-hydrological balance on temperate coniferous forests.

To answer these questions, a highly instrumented long-term monitoring was complemented in the site of the coniferous forest. In the study are, the precipitation (P), temperature (T), and evapotranspiration (ET) were evaluated through eddy covariance technique and SWC variation at several depths. The measurements are routinely performed with additional tools, including water discharge, sap flow, throughfall, fog interception and water holding capacity of lichens. In the context of the interaction of forests and meteorological drivers in conditions of climatic change and, this study aims to understand the ecohydrology of a subalpine forested catchment.

The multi-temporal database on ecohydrology has been generated in the study area with variables with the aim at gathering available meteorological data and integrating them into collected dataset. In the field, the produced database has the potential to become a key instrument for monitoring the protected area and detect responses of coniferous forests to climate change for controlling biodiversity and ecological vulnerability of North Italy. Our database also simulated the land management in the protected area to digitize biodiversity data for climate-environmental analysis.

4. Methods

Recent advances in forest and environmental studies presented numerous computational approaches to solving ecological problems. These include, for instance, programming and machine learning (ML) methods of data processing (Ning et al., 2025; Lemenkova 2019c; Xia et al., 2025), deep learning techniques of data classification (Wang et al., 2025; Lemenkova 2024b), image analysis (Lemenkova 2024a; Vasconcelos et al., 2025), modelling and simulation to reveal trends among the environmental variables (Budeanu et al., 2025; Lemenkova, 2019a, 2019b).

Considering these and similar methods, this study handles datasets with meteorological variables. The data have been collected using measurements by eddy covariance techniques which estimate correlation and eddy flux. This method was selected because it is a key atmospheric measurement approach to compute vertical turbulent fluxes within atmospheric boundary layers. Time course of daily precipitation (P, top left in continuous line for clarity) as well as daily evapotranspiration measured with eddy covariance (ET) and daily transpiration for the old (T_{of}) and young (T_{yf}) forest formations upscaled from sap flow measurements, Figure 1 (top right).

For non-homogeneous contributions of data collection from study areas, the field methodologies were defined and standardized before the onset of data collection activities with relevant harmonization of data. The correlation of daily ET, T_{of}, and T_{yf} with daily P (bottom left) and correlation of daily T_{of} and T_{yf} with daily ET, Figure 1. The position of sensor is reported in Table 1. The method analyses high-frequency data series that focus on evaluating wind, gas, energy, and momentum fluxes of the atmosphere based on the values of these parameters. Table 1 shows the average air temperature (T), air relative humidity (RH), and vapor pressure deficit (VPD) from 30 min data outside and at two heights inside the canopy for the measuring period (15 m and 23 m at the top of the canopy) during the measuring period in summer 2019.

Table 1 Meteorological characteristics (average air temperature (T), air relative humidity (RH), and vapor pressure deficit (VPD) outside and at two heights inside the canopy.

sensor position	T (°C)	RH (%)	VPD (hPa)
outside	11.0 ± 4.8	77.5 ± 16.6	3.5 ± 3.3
15 m	11.5 ± 5.3	89.1 ± 14.2	2.0 ± 3.3

Estimated fog contribution to throughfall in mixed precipitation events in the young and old forest stand is summarized in Tab. 2. Specifically, it shows mean ± standard deviation for absolute amounts. Fog contribution 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.

Table 2 Estimated fog contribution to throughfall in mixed precipitation events in the young and old forest stand.

Days with mixed precipitation	Young forest	Old forest
P measured (mm, see Table 3)	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

The dataset obtained from the eddy covariance measurements (Table 2) was treated using statistical methods. Such approach is used in meteorology to determine exchange rates of water vapour and other fluxes over natural ecosystems and forest stands. The emissions of momentum, heat and water vapour, detected from eddy covariance techniques were quantified to obtain rates of gases from forest, open land and water areas. The processed data were visualised using Python modelling libraries. The dataset from needleleaf forest eddy covariance techniques was evaluated statistically in South Tyrol. Results show that older forests (> 200 years old) are cooler than younger (<30 y.o.) at annual scale.

Table 3 Water components at canopy level roughly divided into months according to sampling dates of the manual throughfall gauges.

Days with mixed precipitation	young forest	old forest
P measured (mm, see Table 3)	460 ± 35	460 ± 35
Total Tf measured (mm)	292 ± 26	216 ± 11
Tf estimated from rain only events (mm)	243 ± 7	184 ± 8
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The latent and sensible heat fluxes of older forests dominate an average cooling effect, which counteracts warming and drying. In this way, older stands play the role of buffers in hydrological and environmental balance. Additional warming effect is further offset by emissivity and incoming radiation. Table 3 shows water components separated into dry and precipitation phases using daily data observation at canopy level. Here, the throughfall and stemflow were measured using gauges, data on interception, and precipitation both inside and outside the forest during dry seasons. The dataset is divided into months according to sampling of the throughfall gauges.

5. Results and discussion

5.1. Age of forest as climate regulator

Forest stand age has a major impact on how forest ecosystems function because it shapes physiological and structural plant features that impact carbon and water budgets. The relationship between tree age and regeneration is impacted by both natural and anthropogenic disturbances. The changes in mountain ecosystems and climate processes affect and determine the age distribution of forests. The potential for improving forest stability and resilience is the shift in tree age distribution brought about by human activity or climate. We examined the effects of forest age on the resilience and stability of forest ecosystems using variables like temperature, evapotranspiration, and precipitation in both young and old coniferous forest stands. The measurements revealed that evapotranspiration played a dominant role in cooling surface temperature, while presence of lichens and age of forests acted together to increase forest surface temperature.

Figure 3 shows the results of the statistical modelling which revealed that older forests are cooler than younger forests at annual scale and that the forest age dominates the warming effect. Figure 3 shows two rows of graphs with the upper one illustrating the time course of daily precipitation (P, top left in continuous line for clarity) as well as daily evapotranspiration measured with eddy covariance (ET) and daily transpiration for the old (Tof) and young (Tyf) forest upscaled from sap flow measurements (top right), Figure 3.

The lower row shows the correlation of daily ET, Tof, and Tyf with daily P (bottom left) and correlation of daily Tof and Tyf with daily ET. This graph well illustrates that evapotranspiration (ET) partitioning separates soil evaporation (E) and plant transpiration (T) components which are is crucial for knowledge about the land-atmosphere interactions. This parameters indicates the health of forest stand and general water budget of the ecosystem. In this graph, we can analyse the mechanism and controls of ET partitioning for boreal coniferous forests of South Tyrolean Alps in heterogeneous environments which until now remained poorly understood.

Figure 4 shows the throughfall in old (of) and young (yf) stand forests against precipitation accumulated to sampling dates. The sampling dates are for the manual gauges measured with manual gauges (top left), automatic gauges (top middle) and all gauges (top right). Correlation of throughfall of old (of, x-axis) versus young (yf, y-axis) stand measured with manual gauges (bottom left), automatic gauges (bottom middle), and all gauges (bottom right).

The error bars show the standard deviation between gauges of each stand in all plots. The analysis of this graph reveals the links between the evaporation from soil or water surfaces (E) and transpiration from coniferous trees at various age (T), as well as evapotranspiration (ET) from the surface water. This link enables to better understand the mechanism of ecosystem functioning and energy balance in the coniferous forests of north Italy, Figure 4.

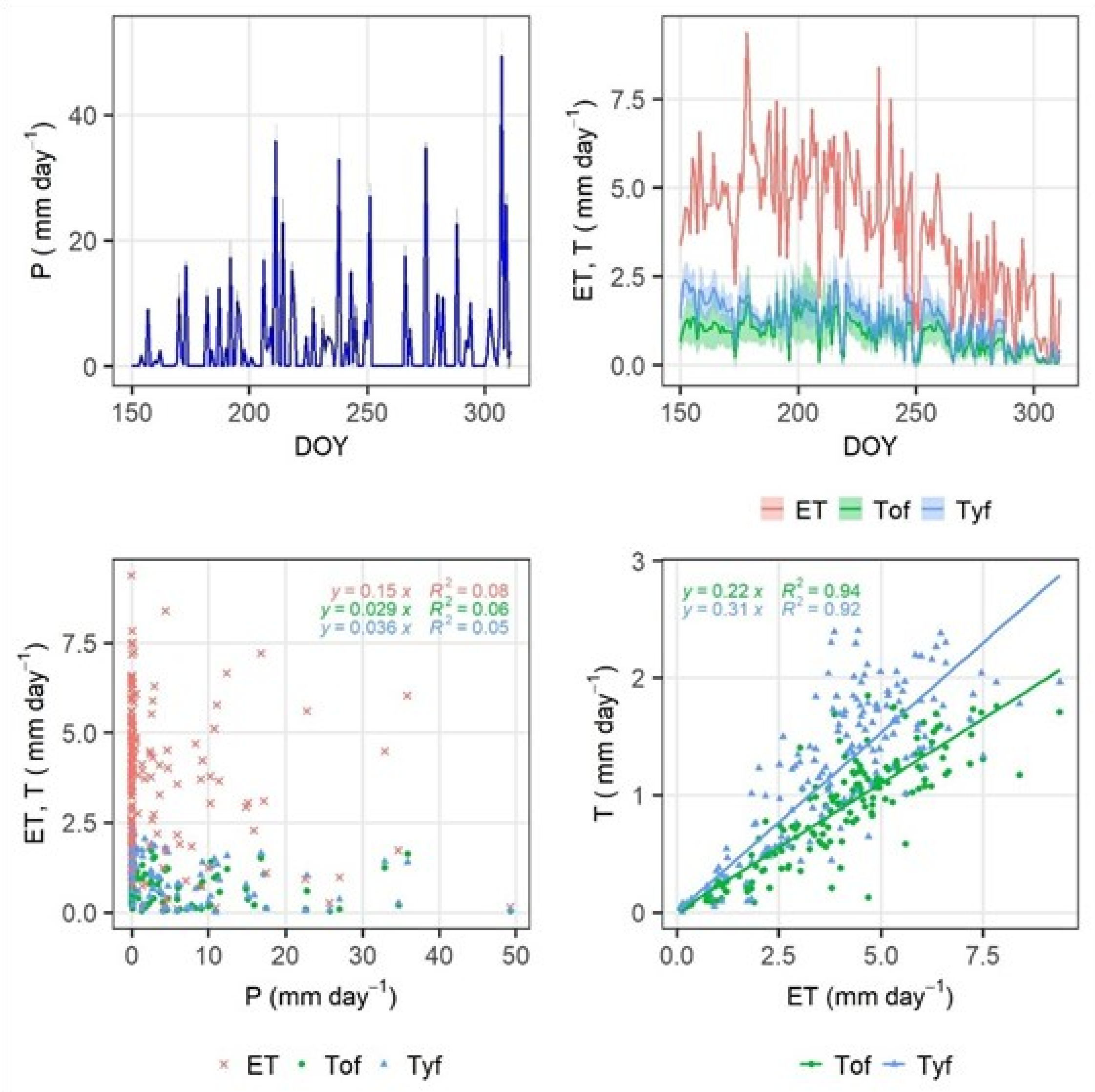

Figure 3 Meteorological parameters (precipitation, evapotranspiration and temperature in young and old coniferous forest stands).

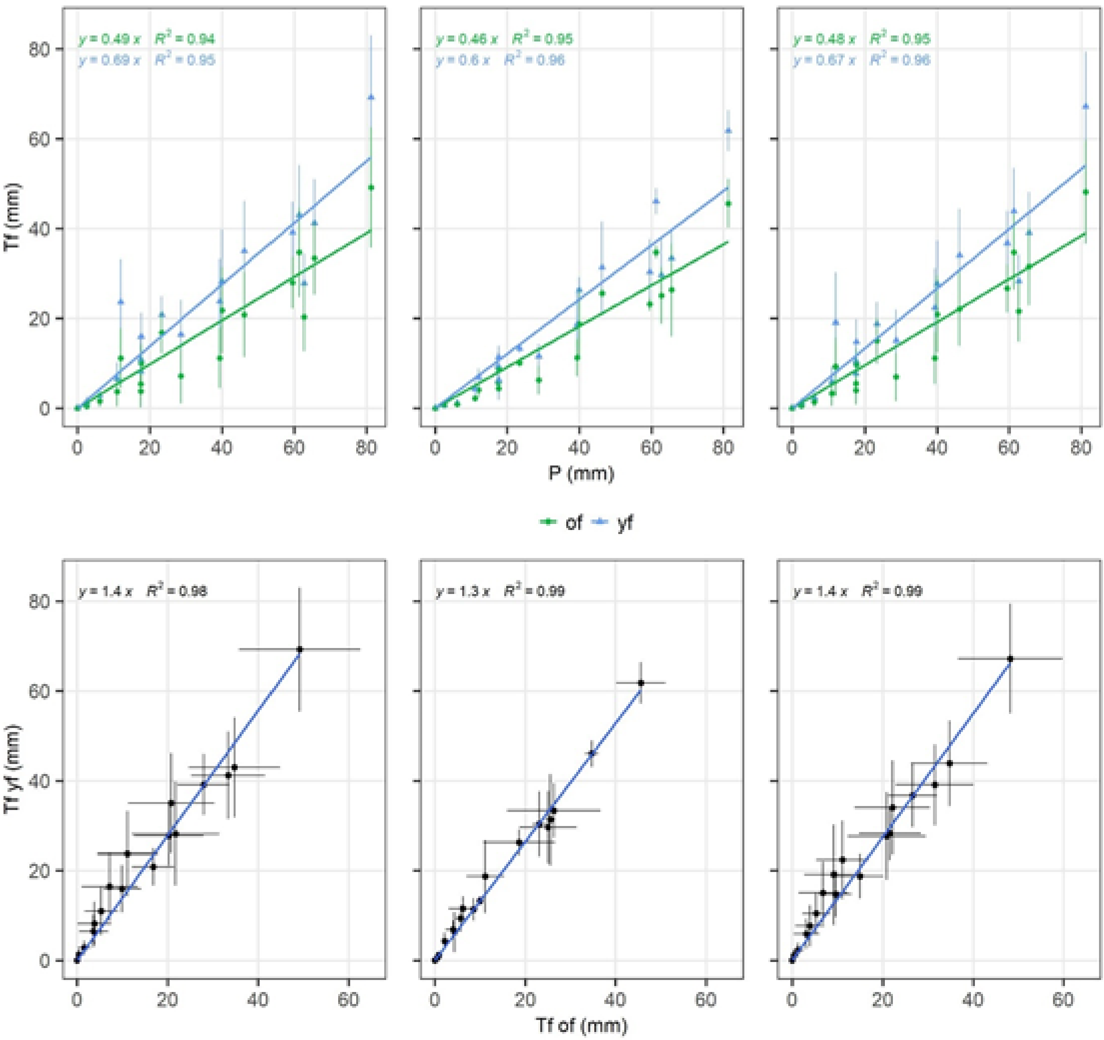

Figure 4 Throughfall in old (of) and young (yf) stand versus precipitation accumulated to samples.

The interception played a dominant role in the precipitation and evapotranspiration partitioning, in the older stand, where it was enhanced by the presence of lichens. Tree transpiration was lower in the young stand and the evapotranspiration of soil and understory contributed considerably to the water balance at both stands. Fog caused additional throughfall in mixed fog and rain precipitation events. Discharge and the change of soil water content played a minor role in the yearly hydrological balance which was almost closed.

Considering that the projected crown area of the sampled tree was approximately 19.6 m^2 (average radius of the canopy 2.5 m), the amount of water held by the tree was 0.63 kg m^{-2} or 0.63 mm. Notably, this amount of water can be refilled by each rain and fog event and is consequently evaporated without stomatal control dependent on VPD. This is known as the function of the forest to respond to radiative forcing by increasing the emission of latent heat instead of sensible heat.

5.2. Linkage between meteorological parameters in forest of various age

The silvicultural practices are significant in terms of age distribution of managed forests. Therefore, understanding the linkage between meteorological parameters in forest of various age reveals the sensitivity of tree age to climate change in the forest carbon budget. This is essential for developing future smart forest management and silviculture. For instance, controlling the age of forest and how they react with climate variables helps to better establish forest growth and composition. In turn, healthy and quality forests are fundamental source of woodlands which support regional economics that depend on forests resources. Therefore, the results of our modelling support devising strategies to enhance forest resilience and stability under climate change as well as regional economics and sustainable development, Figure 5.

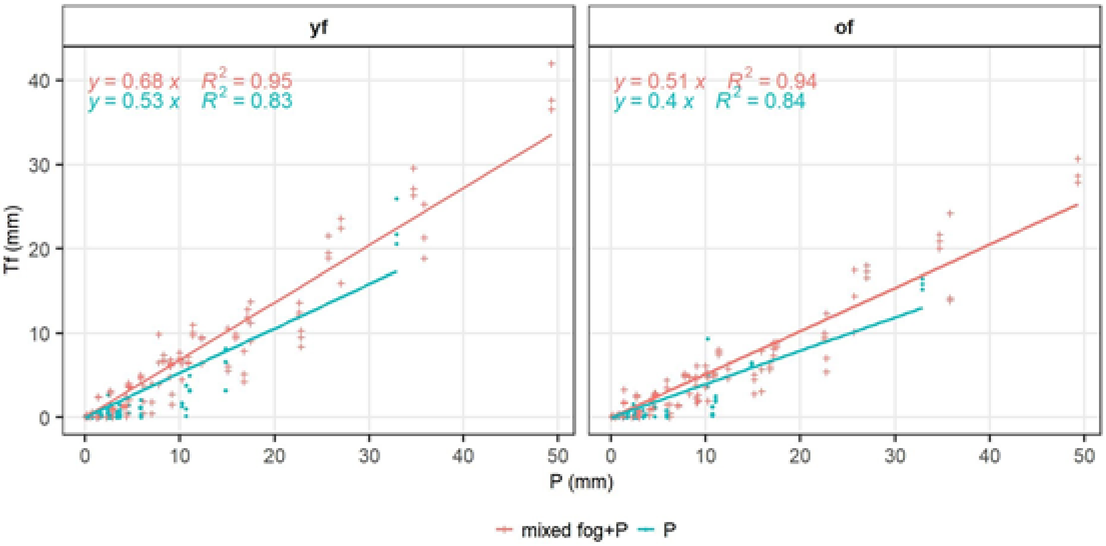

Figure 5 Throughfall versus precipitation during mixed precipitation (mixed fog+P) and rain-only (P) events in the young (yf) and old (of) forest.

In ecohydrology, the partitioning is resolved by distinguishing between transpiration by the vegetation and evaporation from surfaces within the forest. The evaporation from canopy interception can be determined indirectly or modeled, even though sapflow sensors and canopy chambers, for example, can detect soil evaporation and tree transpiration directly (Lemenkova, 2025c). Here, the statistical techniques were applied based on energy balance to elucidate the relative contributions of various hydrological and climate elements to the local surface temperature change brought on by variations in forest age.

In this study, we applied modelling techniques illustrated in the graphs above. The abundance of lichens in the old but not in the young stand could be a major reason for lower throughfall rates indicating a higher interception capacity in the old stand, even though Leaf Area Index (LAI) was similar in both stands. Due to the protected status, we collected lichens from one fallen tree representative of the old forest. This tree held 7.26 kg of dry lichens; 0.71 kg (10%) of them were located on the trunk and the rest on the branches with the highest concentration located at 22 m above the soil (at approximately ¾ of the tree height). Once rewetted, the lichens reached a fresh weight of 19.63 kg, thereby holding 12.37 kg of water; however, they lost ⅔ of that water again within two days when air-dried.

5.3. Water partitioning

Water partitioning in presented in Figure 6 that shows is for the young forest (left) and the old forest (right) for the 5 months measuring period from 2019-5-30 until 2019-11-07. Total precipitation was split into rainfall (P), mixed precipitation (Mixed fog + P) according to fog observations. Interception (I) was calculated as the residual of measured P + mixed fog+P - throughfall (Tf) - stemflow (Sf). Evapotranspiration of soil and understory (Esu) was calculated as the residual of evapotranspiration (ET) measured with eddy covariance for the whole forest minus interception (I) and tree transpiration (T) measured as sap flow. Discharge (DC) and change of soil moisture (dSWC) were also measured for the whole forest, deep percolation was not quantified for the measuring period as ET + DC + dSWC was greater than total precipitation.

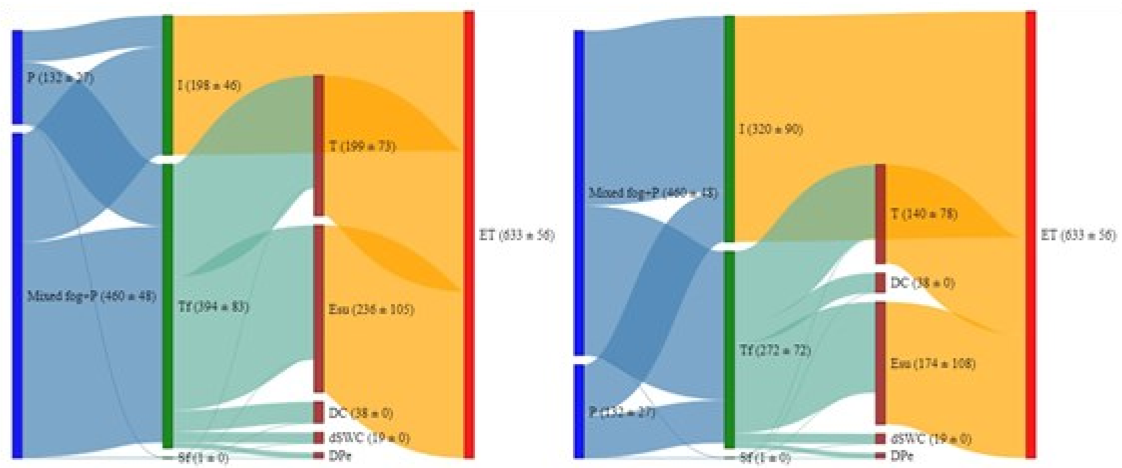

Figure 6 Water partitioning for the young forest (left) and the old forest (right) for the 5 months measuring period from 2019-5-30 until 2019-11-07.

The quality of forests and woodlands strongly depends on the meteorological and environmental conditions. At the same time, forests affect the variability of key climate parameters through maintaining water balance. In this way, evaluating forest ecology with linkage to hydrological balance aims to meet the diverse needs and values of landowners in forest regions and society. Thus, the contribution of forest monitoring goes also to the economic development of timber production, environmental and sustainable goals (wildlife habitat restoration), land and water resources, land cover changes, and tourism recreation in forest areas on a sustainable basis.

Despite the importance of the interaction between forests and regional hydrology, few studies have successfully determined the various components of the water cycle and evapotranspiration partitioning at the basin level on forested terrain. In particular, given the high cloud cover characterizing Alpine mountains, this study evaluated what the direct contribution of fog water might be to the hydrological cycle. Additionally, we explore whether fog might indirectly contribute to ecosystem water availability by promoting the growth of lichens, which can influence the water cycle due to their inherent water retention capacity.

By comparing the relative importance of the hydrological balance, meteorological parameters and other predictors of the environmental dynamics, we disentangled the drivers of water balance in young and old forest stands using Python-based statistical analysis and Sankey diagram. This enabled to better understand the consequence on distribution of lichens, fog and meteorological parameters on water retention capacity in the coniferous forests. Such approach is specifically useful for plant biodiversity and landscape dynamics because it enables to detect trees, vulnerable to local climate effects and hydrological balance. To interpret such trends, quantitative Python-based modelling has been integrated with qualitative environmental analysis. Thus, we employed data analysis methods with ecosystem knowledge in a structured way, allowing a more thorough characterization of the underlying drivers of vegetation dynamics in the Italian Alps.

Finally, the prediction of vegetation change under the effects of water availability (hydrological setting) and climate change (meteorological setting) is possible under different multi-source data scenarios. This enabled to better understand climate vulnerability and vegetation exposure to climate change in selected region of Europe. By combining these data, we contributed to the assessment of the vegetation risks with relation to climate change so to inform ecosystem-level conversation decisions and develop tailored environmental strategies in the boreal mountainous forests of Europe.

6. Conclusion

Nature conservation is increasingly seen as effective environmental solution to counter biodiversity loss in areas affected by climate-related processes, such as fluctuations in temperature and humidity. This study tests the assumptions of climate effects using real-world example of the Alpine ecosystem with dominating spruce species. Using statistical methods of modelling, this study integrated survey data, remote sensing observations, quantitative modelling and qualitative data on environmental preceptors for multi-facetted understanding of the climate-environmental processes. The methodology highlighted the most important determinants of these linkages and creates narratives to uncover the underlying drivers (presence of fog and lichens and their effects on the humidity in old forests). This knowledge is crucial to understand challenges of climatic processes in vulnerable mountainous ecosystems of Europe.

Current study developed the climate-hydrological monitoring and eco-hydrology of Alps to evaluate the contrasting role of age of trees and meteorological parameters on water balance. Subalpine forests in the Alps are fragile ecosystems with high importance for human water resources and the local and mesoscale climate. While previous studies have measured different components of the water balance, little is known about the frequency and influence of fog and the role of forest age in the water balance. Here, we conducted a comprehensive study of a subalpine coniferous forest in the Italian Alps, where a dense, old-growth forest section, intertwined with young patches, was monitored using the eddy covariance technique, tree transpiration sensors, remote sensing images, throughfall, stem flow gauges, water discharge measurements, soil moisture sensors and epiphytes quantification. Specifically, the results revealed that precipitation interception and evapotranspiration partitioning change with forest age. Besides, fog plays a considerable role in the water balance of temperate, coniferous mountain forests, though it appears to be less frequent than in tropical and subtropical could forests.

A statistical Python-based model was used to estimate the impacts of forest age and height of canopy as well as presence or absence of fog on state of regional climate in terms of water balance. We showed that despite absorbing more net radiation the boreal coniferous forests tended to cool T on regular basis, but with a significant effects from forest age and external effects of fog. Specifically, local meteorological setting may lead to a net cooling effect from March to September and a slightly warming effect in other months. From June to September, a cooler and wetter layer was developed over the coniferous forest stands due to high level of transpiration from the canopy. In other months, it was slightly deeper and warmer over the forest with dense canopy than that over the bare lands (without trees). Therefore, the coniferous forests were important in moderating warming trends in temperate subalpine regions.

With respect to project coherence as to the general environmental goals, the presented study matches the resilience goals and strategies on forest protection. With regards to nature conservation and monitoring aims, this study demonstrated relations between the climate and environmental parameters using advanced statistical tools. In this way, it strengthens our understanding of ecosystem functionality in climate context of Alps through modelling of the predictive capacity of climate change effects on coniferous mountainous forests, implementation of the advanced integrated monitoring system that integrates field meteorological measurements with statistical analysis. Such approach contributes to the protecting of green areas in the Alps.

Measurements of the water balance components are usually surrounded by considerable uncertainties and, in hydrological approaches, widely accepted simplifications. Experimental studies where the different components of the water cycle are directly measured are scarce. Frequently, one or more of the components of the balance are assessed indirectly, with a modelling approach. The same happens concerning flux partitioning. Here, diverse techniques of measurements were accepted and integrated using Python-based modelling.

The primary goal of this study is to examine the biophysical mechanisms underlying the effects of forests of varying ages on the local surface temperature and water balance. In order to examine the biophysical effects of forest age changes on local surface temperature, we initially chose five paired neighboring eddy covariance forest sites in South Tyrol that belonged to distinct age classes (> 200 years old and <30 years old). To characterize the growing conditions for lichens in both stands, we measured some meteorological variables inside the forest. The relative humidity was higher within the forest, especially at 15 m, where vapour pressure deficit was lowest. The temperature was not much different outside and inside the canopy. The highest temperature and consequently highest VPD was measured at 23 m but the differences were within the error range. Standard deviations were high, as they were calculated over time, thus included daily and seasonal variability, and were the highest within the canopy. Hence, the meteorological parameters are related to humidity.

The presented study has the objectives of the biophysical monitoring of forest stands in the Alpine environments. It has tackled these objectives in the protected Italian mountain areas covering a wide regional topographic gradient. The area was chosen for having similar environmental features to the typical coniferous forests of North Italy and experiencing analogous environmental and hydrological trends. The concrete steps of the research were separated in various work packages, including data gathering, harmonizing environmental variables in old and young forest stands, creating statistical plots using collected data and analyzing the results on vegetation health with relevant texts. In this project, additional field data were collected to fill potential data gaps on biophysical parameters in forests (presence of lichens on trees, availability of fog and meteorological setting: temperature, precipitation and evapotranspiration).

The analysis of these data enabled to evaluate water partitioning for the young forest and old forest as multi-temporal comparisons (for the 5 months measuring period in season of 2019. Future implications of this work can include integrated data analysis with additional information on land cover types, climate datasets, to fit a time-relevant spatially explicit model quantifying the impact of climate processes on vegetation in forests of Northern Alps. Qualitative data collected by interacting with Eddy covariance measurement tower advanced interpreting the model results. This study also contributed to the analysis of biodiversity trends observed in spruce coniferous forests in the recent years. Finally, this study produced a spatially explicit assessment of the vulnerability of the coniferous forests and exposure of vegetation and ecosystems of North Italy to climate change. This was possible by borrowing concepts and approaches from statistical analysis, hydrological risk science and climate variables.

Future implications of this study include evaluation of vegetation vulnerability in the coniferous forests, exposure and risk of climate change in the Italian mountainous areas and environmental monitoring at regional scale. This study demonstrated that investigating complex environmental problems is based on the multi-facetted understanding of the drivers shaping biodiversity patterns and climate-environmental trends. The future studies can adopt the conceptual and methodological approaches developed in this study. These included four major benchmarks: 1) multi-temporal climate-environmental dataset with data collected during fieldwork in various periods; 2) Statistical models based on Python's libraries; 3) Novel mixed method approach to qualitative-quantitative interpretation of biodiversity and ecosystem trends in coniferous forests; 4) correlation and trend analysis in climate influence and impacts on vegetation. Finally, further works may consider new datasets on biodiversity, remote sensing and land cover monitoring.

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