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Contribution of epiphytes and fog to patterns of atmospheric fluxes in mountainous forests (*Picea abies* L. and *Pinus cembra* L.)

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SUMMARY

Water balance in coniferous forest dominated by *Picea abies* L. and *Pinus cembra* L. is a central process contributing to global carbon and water cycling. Quantifying the roles of the major biotic and abiotic agents that influence water balance, i.e., lichens and fog, is thus important for a better understanding of this process. Methods to quantify water balance, such as evapotranspiration, precipitation, and temperature suffer from several shortcomings, such as destructive sampling or subsampling. We developed and tested a Python-based statistical approach based on computed environmental and climate parameters obtained from Eddy covariance measurements of coniferous forests from a field experiment with dominated by Swiss pine and spruce as major tree species. We quantified the volume of key meteorological parameters in forest canopies with old (> 200 y.o.) and young (< 30 y.o.) trees and relative water vapour volume showing signs of contribution from fog. The data were compared using Matplotlib library of Python for statistical analysis for both types of trees. Fog and lichens were identified with high accuracy and strongly correlated with water content in coniferous forests. Our data show that this is a powerful approach in silviculture for quantifying water balance using Python and statistical analysis of datasets. In contrast to other methods, Python programming libraries offer a flexible yet powerful toolset for data analysis. Additionally, non-destructive field measurements were performed across the entire study area, providing spatially explicit information on forest health. This integrated approach opens a wide range of research opportunities in nature conservation and land management within protected areas of mountainous coniferous forests.

Keywords: data modeling, Python, data analysis, environmental monitoring, forest, landscapes.

INTRODUCTION

The water balance of coniferous forests represents a physical-hydrological phenomenon resulting from climate-driven processes of water accumulation and release through evapotranspiration. This fundamental concept in ecohydrology is reflected in the movement of water among components of the forest ecosystem, each that contributing with different intensity (Bonell, 2002; Kundzewicz et al., 2002). Specifically, the key components include precipitation (Jia et al., 2022; Xu, 2024), temperature (Chen and Zhuang, 2013), evapotranspiration, the age and structure of trees (Bosch and Hewlett, 1982), the presence of lichens (Liu et al., 2021; Wu et al., 2021), and fog (Domen et al., 2014; Fessehaye et al., 2017).

In environmental hydrology, water balance is the result of these interactions between these components, responding to climate change reflected as fluctuations in temperature and precipitation. Measuring water balance using hydrological equipment enables the evaluationof factors that influencewater balance. It also facilitates the assessment oflinks between vegetation and meteorological conditions, which play various roles and contribute to forest hydrological cycle (Muttiah and Wurbs, 2002). Evaluating the role of different components of forest ecosystems and their contributions to the water cycle is effective in different contexts. Examples include environmental monitoring, silviculture (Shen et al., 2025), landscape protection (Delgado-Rodriguez et al., 2025), land management (Dalgleish et al., 2016; Chen et al., 2016) and monitoring the health of forest stands (López Aguirre and Barrios Trilleras, 2024). Other examples include preservation of protected national parks (Ristić et al., 2024; Lemenkova, 2025a), and supporting ecological services for sustainable development (Al-assaf et al., 2014), to name a few.

Forests are biodiversity hotspots that include a high number of endemic species and provide numerous ecosystem services, including maintaining water balance and serving as recreational places (Klaučo et al., 2013, 2017; Shin et al., 2023). Forest water balance is the relationship among precipitation, evapotranspiration, runoff, and water storage within a forest ecosystem, determining how water is distributed and retained over time (Dingman, 2015; Bonan, 2019). Mountain forests, in particular, are characterized by high cloud cover and frequent fog. In these environments, fog adds significant moisture by functioning as precipitation source in horizontal layers. This can affect plant growth, water availability, and the chemical composition of the ecosystem. However, the amount of fog water available for the water cycle in a mountain forest may differ substantially from that of cloud forests (Han et al., 2024). In forest ecosystems with high concentration and constant fog frequency, for-derived moisture may account for up to 49% of the annual water input (Wang et al., 2025). Nonetheless, the role of fog in the water balance of temperate mountain regions, such as the Alps, is still largely unknown.

The Italian Alps feature extensive coniferous forests, particularly at higher elevations, with species like spruce (*Picea* L.), larch (*Larix* L.), and various pines dominating the landscape, often found in mixed forests with deciduous trees at lower altitudes (Leonelli and Pelfini, 2008; Piccini et al., 2023). Forests in the Italian Alps are influenced by convective clouds appearing over mountain peaks in the summer, and thermal inversions, which lead to higher fog occurrence in valleys in the winter (Malek et al., 2014; Bhakare et al., 2024). These high variations in cloudiness at small spatial scales affects the assessment of evaporation fluxes, which include large uncertainties and are difficult to assess and interpret. In South Tyrol, low vapour pressure deficit (VPD) and low atmospheric evaporation fluxes are frequently observed. These are important features useful to assess the importance of fog in the water balance.

Objectives and goals: Alpine mountain forests are characterized by high cloudiness and humidity. Although there are many publications related to mountain forest hydrology, there is a lack of related publications on the quantity of fog water contributing to the water cycle and how it varies acrossthe mountain forests. To address this gap, the objective of this study is to analyse the role of fog and lichens in forest hydrology. Specifically, the goal is to model the impact of fog and epiphytes on the annual and seasonal water budgets in the mountainous forests of northern Italy. A particular focus is placedon analyzing the moisture in the canopy structures of coniferous trees.

To achieve these goals, the role and contribution of fog were estimated based on its impact on throughfall, following established methods in silviculture. The research hypothesis is that fog has an impact on the annual and seasonal water budget, which is explained by air physics. Additinally, we suggest that the increase in water content follows an exponential relationship with air temperature and the amount of precipitation (including both liquid and solid forms). So far, little is known about fog and dew contribution in the water balance if enough moisture is present within canopy structures.

Moreover, there is a potential influence of lichens on the water balance because their occurrence is associated with fog and tree age. Stands with older trees (≥ 200 years) have a higher interception capacity and lower throughfall rates than younger stands, due to the presence of epiphytic lichens in older forests. The amount of water intercepted by the forest canopy varies with its age, structure and leaf type. It is also affected by the presence of mosses and epiphytes which may intercept high amounts of water. Thus, they store water inside the forest, sustain evapotranspiration and increase air humidity. Rain and clouds maintain almost zero VPD conditions in forests. This poses little water stress to leaves, and particularly to epiphytes (lichens) which contribute to the water balance. This is the case for temperate mountain forests, where needles can live for years and epiphytes develop on boles and branches of old trees. In aged forests, lichens continue to grow on old plants and increase the interception capacity, when the stand leaf area index (LAI) has already reached its maximum.

MATERIAL AND METHODS

The study area is located in the coniferous forests of the Dolomites, northern Italy (Figure 1). The forest is of natural origin and managed for timber production. The traditional harvest method creates small gaps, cca. 50 m wide, through the thinning of surrounding trees. This approach results in a heterogeneous vegetation structure, where nearly even-aged tree groups contribute to an uneven-aged structure at the broader landscape scale. At the study site, two

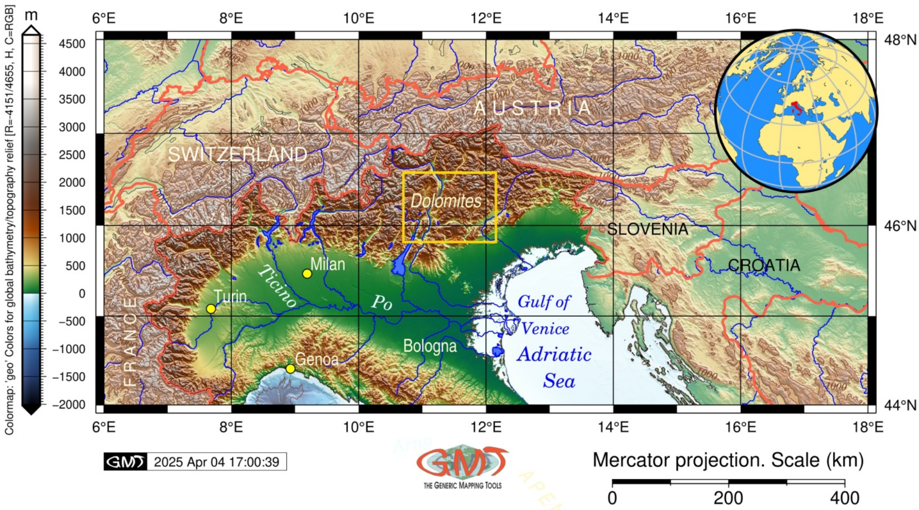

Figure 1. Study area located in northern Italy, coniferous forests of South Tyrol, the Dolomites (yellow square). Cartographic software: Generic Mapping Tools (GMT) version 6.5.0. Map source: Author.

groups of trees were investigated: 1) a large group of predominantly spruce trees approximately 200 years old, and 2) a second group of young trees, around 30 years old. In both stands, parts of the living crown frequently reached the ground, regardless of tree age.

The location of this study is in South Tyrol, in the Italian Alps (1735 m a.s.l., 46°35'11"N, 11°26'00"E), Figure 1. The typical species are 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* L.) individuals were also sparsely present. The dominant tree height was approximately 29 m. The understory consisted mainly of alpenrose (*Rhododendron ferrugineum* L.) and blueberry (*Vaccinium myrtillus* L.). Intervening grasslands were dominated by wavy hair-grass (*Deschampsia flexuosa* (L.) Trin). Capacity of the forest to intercept water in the canopy was quantified in two different forest stands, 200-year-old and 30-year-old.

The water partitioning using Eddy covariance techniques was estimated at the catchment level for the old and young forest stand (of and yf) for five months during the growing season. First, a linear regression equation was determined between the 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). 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 product of precipitation and the slope of the throughfall to precipitation equation from rain-only events.

Total precipitation (P) was split into rain (Pr, mm) and mixed precipitation (rainfall + fog) (Pm, mm) (only 9 days with fog), canopy interception (I, mm) was calculated as P – throughfall (Tf) - stemflow (Sf), using instrument characteristics provided in Table 1. The data were modelled using Python statistical libraries (Lemenkova, 2020, 2025b). Several metrics were used to calculate the density of drained lakes: tree age and the number of rainy days and presence of lichens on tree trunks. The sampling data were calculated using Matplotlib library as the ratio of variables and visualised in the graphs. These models illustrate the correlation patterns between the parameters and the likelihood of fog to contribute to water balance events in different regions. Based on the eco-hydrological delineation, the relationships between the forest hydrology, occurrence of fog and presence of lichens were investigated.

Table 1. Technical characteristics of the equipment used to calculate the water balance.

Description	Height above ground (m)	Nr. sensors	Instrument uncertainty (systematic error, %)
Evapotranspiration with Eddy covariance	33.7	1	+ - 8.8%
Global and diffuse radiation	40.3	1	+ - 5%
Net radiation	-	1	-
Relative humidity	33	1	
Precipitation	2	1	+ - 3%
Fog frequence (visibility)	32	1	
Sap flow	5 spruce trees	2	+ - 20%
Temperature inside the canopy	15.23	2	0.1%
Humidity inside the canopy	15.23	2	3.0%
Precipitation - below canopy, throughfall	0.3	16	+-1
Soil water content	0.05, -0.10, -0.20, -0.50, -1.00	5	2.5%
Water discharge	0-2	1	0.1%

Evapotranspiration (ET_EC) was measured using eddy covariance and evapotranspiration of the soil and understory (Esu) was calculated as the residual of ET tree transpiration (T) measured with sap flow sensor (Table 2), minus the evaporation of intercepted water (I) calculated from precipitation partitioning. According to the importance of water conservation in diverse regions, estimating the soil characteristics for environmental monitoring under statistical analysis is essential (Lindh and Lemenkova, 2023a,b). Therefore, we evaluated soil engineering characteristics, as well as its moisture level and temperature.

Table 2. 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 from 25 May to 7 November 2019.

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

The hydrological measurements were done using the instruments used for measurements. The evapotranspiration was measured using Gill HS100 (Gill Instruments Inc. + LI 7500 (LiCor Biosciences); global and diffuse radiation were measured using DeltaT SPN1 (Delta Devices); net radiation was estimated by CNR4net radiometer (CNR4; Kipp and Zonen, Delft, the Netherlands); hydrological parameters were estimated using thermo-hygrometer; precipitation was measureed using Geonor T200b (Geonor); sap flow was estimated using tissue heat balance sensors (EMS51; EMS Brno, Czech Republic). Discharge (DC) and change of soil moisture (dSWC) were also measured for the entire forest. Local trees and spruces in the study area were characterized by an almost columnar shape. This shape and the high LAI (4.74±0.88 for the 200-year-old stand and 4.65±0.86 for the 30-year-old stand), created peculiar microclimatic conditions within the crown, favoring lichen growth. The soil has developed on top of a layer of glacial till, approximately 1 meter deep, which rests on a porphyry bedrock The soil was sampled and classified as Haplic Podzol, according to the FAO taxonomy and consisted of 49% sand, 39% silt, and 12% clay.

Meteorological variables were analysed to understand the meteorological conditions during dry and wet weather, and especially during days with fog presence (visibility below 1 km). The ratio of diffuse to the total global radiation, the VPD, and relative air humidity (RH) were selected to characterize hours and days without precipitation, with fog-only, with rain-only and with mixed precipitation (fog and rain) during the first half of 2015 when half-hourly photos were available from a phenological camera directly at the site. The relationship between precipitation type and three meteorological drivers was used to predict the occurrence of fog and mixed precipitation. These predictions were then compared with fog observations from a public webcam located 3 km away and 300 m lower in elevation than the study site.

The role of lichens in the water balance was assessed by measuring air temperature and humidity inside the tree crown and the water storage capacity of the lichens at two different tree heights: 15 m and 23 m at the top of the canopy. To characterize the growing conditions for lichens, meteorological variables were measured inside the canopy. The relative humidity was higher within the forest, especially at 15 m, where VPD was the lowest. The temperature was not significantly different outside and inside the canopy. The highest temperature and consequently highest VPD was measured at 23 meters, but the differences were within the error range. Standard deviations were high, as they were calculated over time, thus including daily and seasonal variability, and were the highest within the canopy at 23 m. Therefore, the presence of lichens is related to humidity and tree age.

The abundance of lichens in the old forest stand is a major reason for the lower throughfall rates, because it is related to a higher interception capacity in the old stand. The systematic survey of lichens was performed from the tree representative of the old forest. This tree held 7.26 kg of dry lichens; 0.71 kg (10%) of them was located on the trunk and the rest on the branches with the highest concentration located at 22 m above the soil (at cca. 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 approximately two-thirds of that water again within two days when air-dried.

Following collection, the water storage capacity of the lichens was assessed in spring on a tree with a height of 28 m and a DBH of 53 cm, which is representative of the old stand. To estimate the lichen weight, the tree was divided into three-meter sections. In each section, all the branches were counted and all lichens present above a single randomly selected branch were collected, together with the lichens growing on half of the main stem. In the laboratory, the lichens were wetted until saturated with water and then weighed to assess the fresh weight. They were then dried in the oven at 45°C until a constant weight was achieved and then weighed again to assess their dry weight. The data in tabular format was modelled using Python statistical analysis (Lemenkova, 2019). 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 the measured throughfall (Table 3).

Table 3. Estimated fog contribution to throughfall in mixed precipitation events in the young forest (trees of < 30 y.o.) and old forest stand (trees of > 200 y.o.).

Days with mised precipitation	Young forest (< 30 y.o.)	Old forest (> 200 y.o.)
P measured	459.7	459.7
Total Tf measured	291.9	216.4
Tf estimated from rain events (mm)	242.6	184.1
Fog contribution in mised events (rain and fog, mm)	70.3	52.9
Tf/P (%)	63.5	47.1
Estimated rain only Tf/P (%)	52.8	39.6
Estimated fog (Tf/P, %)	15.3	11.5
Rain contribution to Tf (%)	83.1	84.1
Fog contribution to Tf (%)	24.1	24.4

To better understand fog occurrence, the relevance of the measured meteorological conditions was compared during periods with dry conditions (dry), fog (less than 1 km visibility) and rainfall. These included such parameters as relative humidity, temperature, radiation, wind speed and direction, ratio of diffuse to total global radiation and vapor pressure deficit (VPD). The influence of aged tree vegetation in the water balance was studied by estimating and comparing water interception, epiphyte composition and temperature at different heights with an adjacent young canopy forest. Total evapotranspiration was measured using eddy covariance and transpiration with sap flow sensors. Additional measurements at the soil level were performed in an old and young forest, in which we measured the soil moisture. Water discharge was measured at the catchment level.

The diameters and heights of the trees in the research area have been measured every ten years, while the diameter of a subset of trees is measured annually by manual dendrometers. The most recent inventory (tree height, size, and position) was performed with the TruPulse sensor. In addition, tree size was assessed during summer using a laser technique. The higher water storage capacity of the old stand did not depend on the LAI, which was almost identical in the two stands, but on the other structures, mainly epiphytes. Such organisms, typically represented by filamentous lichens, such as *Evernia divaricata* and *Pseudevernia furfuracea*, were relevant for the water cycle in the old section only and had a water-holding capacity of 0.6 mm for each precipitation event.

The periods characterized by dry conditions were compared against the days with fog and with rain, by including both the observation (obs) and the prediction (pred) periods to assess the accuracy of our predictions. The number of days characterised by dry conditions, fog, precipitation (rain or snowfall), and mixed precipitation were calculated. Three representative time periods from late May to early July, mid-July to early September and from mid-September to early November were selected to evaluate meteorological conditions. The measurements on global radiation included data on the total global radiation in the top row, diffuse global radiation in the middle, ratio of diffuse global radiation to total global radiation, temperature and relative humidity. Besides, the measurements were taken during dry, fog, and precipitation periods as well as times with mismatches between observed and predicted fog.

To characterize the growing conditions for lichens, we measured some meteorological variables inside the forest. The relevance of this interception capacity was particularly high when precipitation was light (based on field observations). In this case, the liquid water was used to refill the canopy and soil reservoirs, without being lost as runoff. This large amount of water intercepted by the canopy, which represents most of the liquid precipitation in the old forest stand, is then locally re-emitted as evaporation without stomatal control. In addition, in some ecosystem types, it has been shown that part of this water and fog can be directly taken by the plant for its needs. To estimate fog water, the fog was derived from the comparison of the gross and net precipitation.

RESULTS

The throughfall in old (of) and young (yf) stands versus precipitation accumulated to sampling dates are shown in Figure 2. Specifically, it shows the correlation of throughfall measured with manual gauges (top left), automatic gauges (top middle) and all gauges (top right).

Throughfall rates relative to precipitation were higher in the young than in the old stand (Figure 2) even though the LAI in both stands was similar. Throughfall variability was higher in the manual gauges than in the automatic ones, as they covered a higher small-scale variability of PAI/LAI. A strong linear correlation ($R^2 > 0.93$) was found between throughfall and precipitation for both stands and no clear increase in throughfall ratio with P. Only the last data point with the highest amount of throughfall and P was clearly above the linear regression line, indicating that the limits of the canopy's interception capacity were reached. The correlation between old and young stand throughfall was very high (Figure 2). The interception was found to play a dominant role in the precipitation and evapotranspiration partitioning, especially in the older stand, where it was likely enhanced by the presence of lichens.

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. An independent measurement of soil/understory ET using small-scale lysimeters or

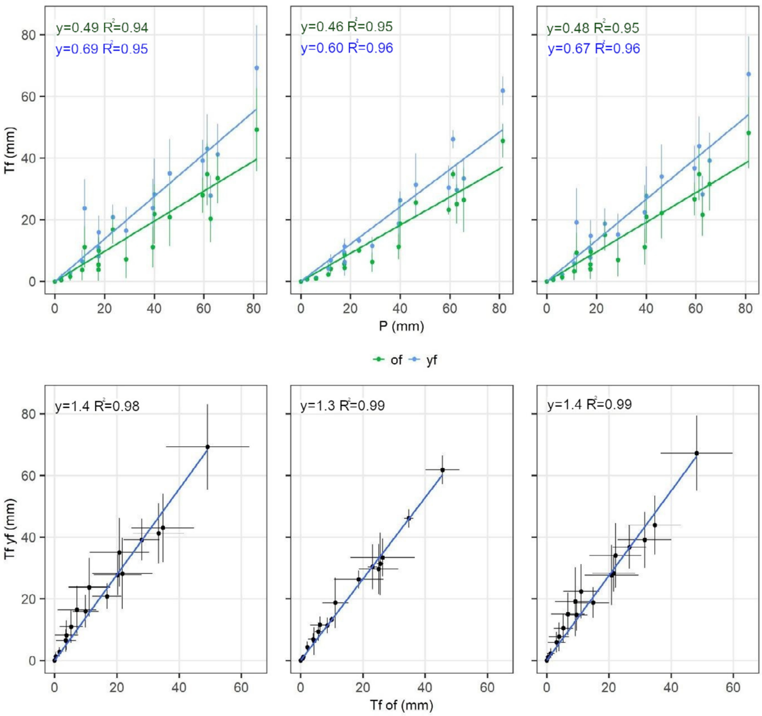

Figure 2. Climate parameters for old (of) and young (yf) forest stands: throughfall and precipitation.

canopy chambers could provide additional information. Evaporation as part of the water cycle 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 explains the low transpiration/ET ratios. Tree transpiration was surprisingly lower in the young stand and the evapotranspiration of soil and understory contributed considerably to the water balance of both stands. Correlation of throughfall of old (of, x-axis) versus young (yf, y-axis) stands was 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. Fog caused additional throughfall in mixed fog and rain precipitation events.

The results of measured water components were split into monthly periods to adjust to the sampling periods of the manual throughfall gauges. The analysis of these results shows that P increased from June to October, while ET was high until September, but decreased strongly afterwards. The Tf/P ratio was higher in autumn (September and October) than in the summer, except for June in the old forest stand. Correspondingly, the interception rate (I/P) was lower. This should be associated with higher P, but also with more mixed precipitation days observed in the autumn. Additionally, stemflow, which was similar for both stands, increased from June to October, but was overall too low to play a major role in the water balance. The discharge and the change of soil water content played a minor role in the yearly hydrological balance which was almost closed. This study revealed that precipitation interception and evapotranspiration partitioning change with forest age, and that 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 (Figure 3). Estimated fog contribution to throughfall in mixed precipitation events was found to be more relevant in old forest stand compared to the young one (mean ± standard deviation for absolute amounts).

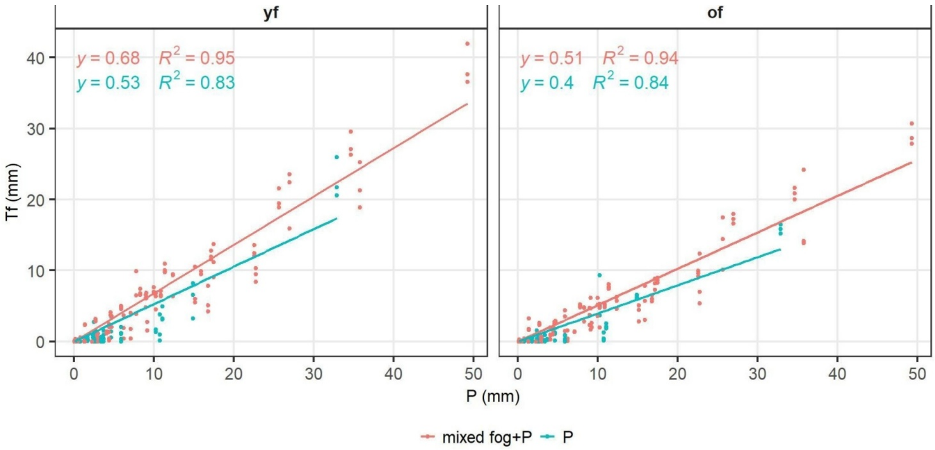

Figure 3. Throughfall versus precipitation during mixed precipitation (mixed fog + P) and rain-only (P) events in the young (yf) and old (of) forest stand.

As expected, the relative humidity was higher within the forest, especially at 15 m, where VPD was lowest. The temperature was not significantly 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 capturing both daily and seasonal variability, with the highest values observed within the canopy at 23 m. Hence, the presence of lichens is more related with humidity than with temperature. Furthermore, fog was not considered in previous studies. Thus, the present findings highlight fog as a critical, previously overlooked component, key to understanding both soil water recharge during days with mixed precipitation and the redcution of evaporative demand during dry periods in the studied Alpine ecosystem (Figure 4).

Moreover, the observed data demonstrated several differences in the ecosystem water partitioning at the catchment scale. Specifically, the difference were particularly evident over the five-month measuring period when comparing the young and old forest stands. Throughfall and transpiration rates were higher in the young forest, leading tolower interception, calculated as the residual of total P minus Tf minus Sf. Since intercepted water eventually evaporates back into the atmosphere, interception accounted for a major part of ET, accounting for 54% in the old forest and 33% in the young forest.

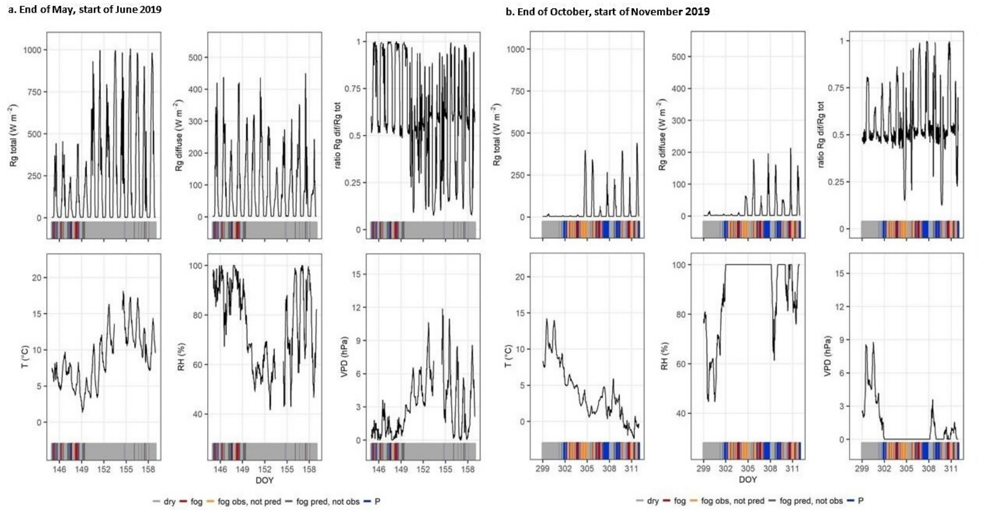

Figure 4. Time course of global radiation (total global radiation top-left, diffuse global radiation top-center, ratio of diffuse to total radiation top-right), air temperature (bottom-left), air humidity (bottom-center) and vapor pressure deficit (bottom right) during a foggy period in late spring, end of May, the start of June (a) and end of October, the start of November 2019 (b).

DISCUSSION

Regarding the hydrology of the Alpine forest, fog is the missing link in understanding the water balance and water cycle. In forests, fog represents a significant component of the annual water input, contributing between 0.2–4.0 mm day^{-1} in subtropical and tropical cloud forest environments. Fog accounts for more than half of the precipitation input to the upper montane cloud forest. Though the water input from fog-only events at our site remained unknown, fog clearly contributed during mixed fog and rain precipitation, where it was estimated to cause a 24% increase in throughfall compared to rain-only events. The ratios of transpiration measured with sap flow to evapotranspiration from eddy covariance (T/ET = 22% for of, 31% for yf) or to total precipitation (T/P = 24% for of, 34% for yf) ratio were low for both stands, compared to those in other conifer forests. On the other hand, our high ratios of interception to precipitation (I/P = 54% for of, 33% for yf) and ET (I/ET = 51% for of, 31% for yf) were in the upper range compared to the I/P values of 17-45% found in the literature. This was likely caused by the denser stand structure compared to boreal or higher-elevation conifer forests. Additionally, lichens played an important and underestimated role in the older parts of our forest.

This study demonstrated that fog has an influences the annual and seasonal water budgets in temperate mountain forests, as the potential water content of air decreases exponentially with lower temperatures. Moreover, fog has a noticeable impact under certain meteorological conditions. Besides, fog appears to increase interception capacity and reduce throughfall rates in younger stands, in part due to the presence of epiphytic lichens in older forests. In this context, a positive feedback loop may be established between tree age and evaporation fluxes.

CONCLUSION

Subalpine forests in the Alps are fragile ecosystems with high importance for human water resources and the local and mesoscale climate. In addition, soil and climate characteristics play vital role both in natural landscapes and social infrastructure for sustainable development (Lindh and Lemenkova, 2022a,b; Kabelka et al., 2025; Bai et al., 2025). While previous studies have investigated different components of the water balance (Feng et al., 2025), the frequency and influence of fog, as well as the role of forest age in the water balance, remain insufficiently understood. We conducted a comprehensive study in a subalpine coniferous forest in the Italian Alps, characterized by a dense, old-growth forest section, intertwined with young patches, which followed the existing studies on environmental modelling (Huang et al., 2025). The data were monitored using the eddy covariance technique, tree transpiration sensors, throughfall and stemflow gauges, water discharge measurements, soil moisture sensors, and epiphytes quantification.

In this study, we demonstrated that forest age is a potential climate regulator, as old forests contribute more to the water balance. Beyond the physiological aspect of plant water use, the capacity of intercepted water to act as a climate regulator at a local scale and the mesoscale is climatologically relevant. For instance, one mm of water at 20°C represents 44.2 W m^{-2} of latent heat, which is emitted instead of sensible heat, thereby reducing the ambient temperature and increasing the availability of atmospheric water vapour. The role of fog is primarily to sustain this positive feedback in the water cycle, favoring the presence of dense vegetation and lichens, and increasing water vapour availability. Environmental modelling and water balance assessments using geospatial data increase our understanding of processes and correlations between parameters (Lemenkova, 2022a,b; Prodromou et al., 2025; Uyar and Uyar, 2025). Modelling, measuring and analyzing data for better understanding of climate change and effects of variables to the hydrological balance is crucial. As we are now facing a reduction of water vapour in the air with possible future disruptions of the positive feedback loop in the water cycle in terrestrial ecosystems, the presence of old-growth vegetation represents a critical element for climate regulation in the Alpine region. This evidence is in line with recent studies indicating the capacity of natural forests to regulate extreme heat conditions.

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Uticaj epifita i magle na atmosferske flukseve u planinskim šumama (*Picea abies* L. and *Pinus cembra* L.)

REZIME

Vodni bilans u četinarskim šumama u kojima dominiraju *Picea abies* L. i *Pinus cembra* L. je centralni proces koji doprinosi globalnom kruženju ugljenika i vode. Kvantifikacija glavnih biotskih i abiotskih agenasa koji utiču na vodni bilans, tj. lišajeva i magle, imaju ključnu ulogu u razumevanju ovog procesa. Metode za kvantifikaciju vodnog bilansa, kao što su evapotranspiracija, padavine i temperatura, imaju nekoliko nedostataka, kao što su destruktivnost uzorkovanja ili poduzorkovanja. Razvili smo i testirali model zasnovan na Pythonu, na osnovu izračunatih parametara životne sredine i klimatskih parametara dobijenih merenjima Eddy kovarijanse kod četinarskih šuma gde su dominirali švajcarski bor i smrča kao glavne vrste drveća.

Kvantifikovali smo zapreminu ključnih meteoroloških parametara u krošnjama šuma sa starim (>200 godina) i mladim (<30 godina) drvećem i relativnu zapreminu vodene pare koja pokazuje znake doprinosa magle.

Podaci su poređeni korišćenjem Matplotlib Python biblioteke za statističku analizu za oba tipa drveća. Magla i lišajevi su identifikovani sa visokom tačnošću i potvrđena je visoka korelisanost sa sadržajem vode u četinarskim šumama. Dobijeni podaci su pokazali da je ovo moćan pristup u šumarstvu za kvantifikaciju vodnog bilansa korišćenjem Pythona i statističke analize skupova podataka. Pored toga, nedestruktivna terenska merenja su izvršena na celom području istraživanja, pružajući prostorno eksplicitne informacije o zdravstvenom stanju šuma. Ovaj integrisani pristup otvara širok spektar istraživačkih mogućnosti u zaštiti prirode i upravljanju zemljištem unutar zaštićenih područja planinskih četinarskih šuma.

Ključne reči: modeliranje, Python, analiza podataka, monitoring životne sredine, šuma, pejzaži.