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# ON FOREST HYDROLOGY IN SOUTH TYROL: PROCESSES, MODELLING AND ASSESSMENT

## SUMMARY

This article presents the investigation of forest–hydrology links in South Tyrol, Dolomite Mts, north Italy. Specifically, the study focused on investigation of the effects of old (> 200 years) and young (< 30 years) forests in regulations of climes. To this end, several key meteorological parameters were evaluated and analysed statistically: evapotranspiration, precipitation, temperatures and water flow. Additionally, the role of fog in distribution and percolation of water was investigated. Dominated species are spruce *Picea abies* (L), 12% Swiss stone pine (*Pinus cembra* L.), and 3% European larch (*Larix europea* L.) trees, as well as Scots pine (*Pinus sylvestris* L.) and European rowan (*Sorbus aucuparia*), presented sparsely. The statistical analysis performed using Python tools revealed to what extent forests increase or decrease streamflow, and mitigate the temperature and regulate precipitation. In this way, coniferous foretss reduce floods, and increase dry season flows. The effect of old and young coniferous subalpine forest was studied with respect to rainfall in varied meteorological settings (dry and wet days). The paper contributes to the development of land management and silviculture.

**Keywords**: forest, Alps, modelling, statistical analysis, data modelling

## INTRODUCTION

Coniferous forests present valuable resource for socio-ecological systems. For economy, they are sources of timber and forest products, for environment, they play important role of climate regulator (Li *et al.*, 2025; Klaučo *et al.*, 2013; Zhang *et a*l. 2025a). For biodiversity, forest provide habitats for rare species. For the cultural well being, forests play important role in tourism and recreation (Klaučo *et al.*, 2017). Besides, forests have a crucial role in hydrological water cycle mitigating climate effects such as droughts and rise or decrease of temperatures and precipitation. The Alps represent an essential source of water availability in Europe, a role expected to become even more crucial under climate

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change conditions. Vegetation interacts profoundly with the water cycle, influencing both water availability for human needs and the distribution between sensible and latent heat (Lemenkova, 2024a, 2025a). Therefore, it interacts with the radiative forcing feedback mechanism. Despite the importance of this subject, few studies have successfully determined the various components of the water cycle at the basin level on vegetated terrain (Cui *et al.,* 2025; Ignatius *et al*., 2025; Lemenkova, 2023b, 2024b; Rodman *et al*., 2021). In particular, given the high cloud cover characterizing the Alpine mountains, we ask what the direct contribution of fog water might be to the hydrological cycle. Additionally, we explore whether fog might provide an indirect contribution to ecosystem water availability by promoting the growth of epiphytes and lichens in particular, which can influence the water cycle due to their inherent water retention capacity.

In the European mountains, including Alps, the subalpine elevation belt is mostly covered by forests dominated by conifers. Coniferous mountain forests are of essential importance for water provision with an impact extending far wider than their actual range (Qiu *et al*., 2022). However, landscapes are also strongly affected by climate change with past and projected warming exceeding the global average (Lemenkova 2023a; Wang *et al*., 2025). The eastern part of the Alps is particularly humid and is dominated by spruce forests. In South Tyrol, spruce forests cover 178,000 ha, i.e., 52.8% of all the forests in the region, which is covered by forests on 45.7% of its surface.

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 (Lemenkova, 2022a, 2022b). In particular, given the high cloud cover characterizing the Alpine mountains we ask what the direct contribution of fog water might be to the hydrological cycle. Additionally, this paper explores if fog might contribute to ecosystem water availability by promoting growth of lichens, which can influence the water cycle due to their inherent water retention capacity.

Experimental studies where the different components of the water cycle are directly measured are scarce. Frequently, one or more of the components of the ecosystem and water balance are assessed indirectly, with a modelling approach (Singh *et al*., 2011; Lemenkova, 2024e; Felipe-Lucia *et al*., 2022). The same happens concerning flux partitioning (Huang *et al*., 2025). In ecohydrology, the partitioning is resolved by separating evapotranspiration into evaporation from surfaces inside the forest and transpiration by vegetation. While tree transpiration and soil evaporation can be measured directly through sapflow sensors and for instance canopy chambers, evaporation from canopy interception can still only be estimated indirectly or modelled (Hou *et al*., 2021).

Thus, there are still major uncertainties, for example, concerning the rate of wet canopy evaporation estimated from eddy covariance measurements (Zhang *et al.,* 2025b) or as differences between precipitation, throughfall and stemflow, or using the conventional Penman-Monteith-equation (Meng *et al*., 2025). This paper evaluates the contribution of fog to water input. Using data modelling, it was also evaluated, to what extent the fog can represent an additional source of water, not quantified by pluviometers, to the overall water input.

## Study area

The experiment was conducted in the Dolomites massif, South Tyrol, northern Italian Alps (the mean topographic elevation is 1735 m a.s.l., the coordinates are 46.586389 N, 11.433333 E for central location), Figure 1.

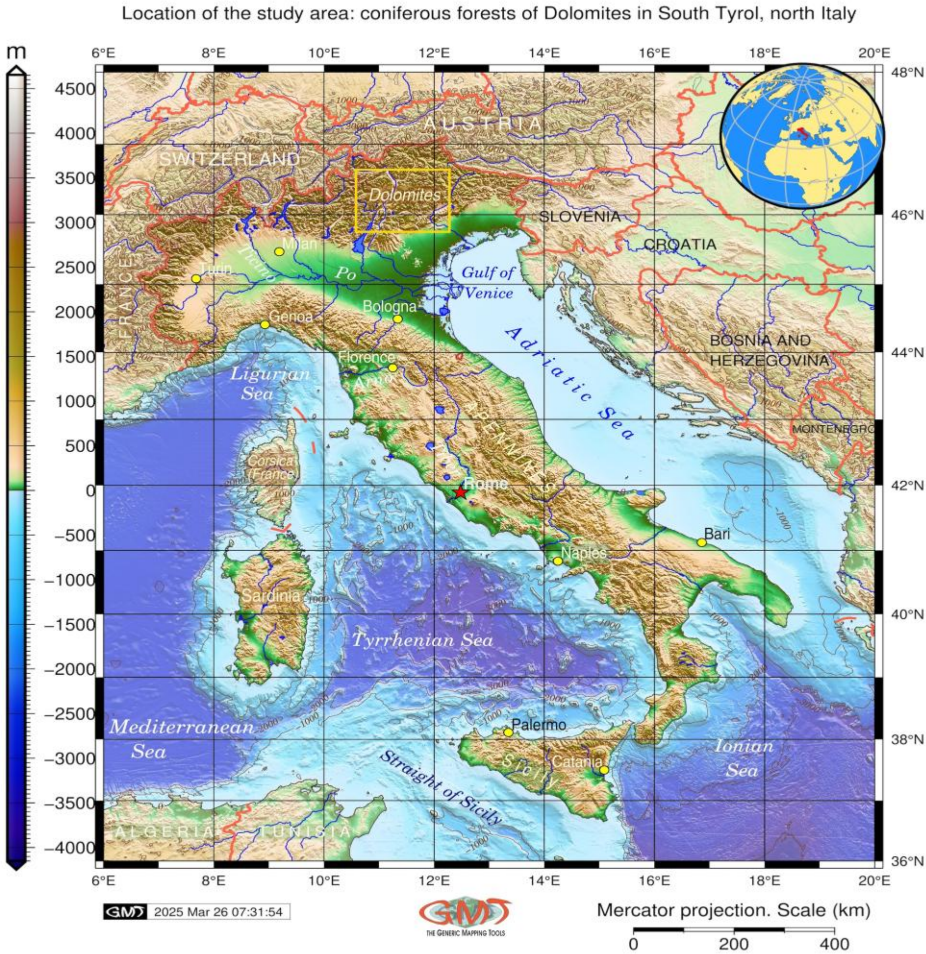


Figure 1. Topographic map of the study area. Source: author

The site, IT-Ren, provides data for several monitoring networks, including Fluxnet, ICOS (https://www.icos-cp.eu/), and Lter (https://www.lter-europe.net/). The catchment has an area of 0.44 km2. At the site, it is present a 40 m tall tower where eddy covariance measurements are routinely performed giving the information on evapotranspiration at a half-hour time step. The water basin where the experiment was conducted was measured using the local digital elevation model using ArcGIS software (ESRI, Redlands, CA, USA).

The soil has developed above a layer of glacial till, with a depth of approximately 1 m, placed on top of a porphyry bedrock. The soil was classified as Haplic Podzol according to the FAO soil taxonomy (FAO, 1998) and on average consisted of 49% sand, 39% silt, and 12% clay, Figure 2.


Figure 2. Fieldwork measurement in South Tyrol: coniferous forests of 2 types of age: old stands (>200 years old) and young stands (<30 years old).

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

The forest is of natural origin and managed for wood production. The traditional harvest method creates small gaps, approximately 50 m wide, and involves the thinning of surrounding trees. The result is a heterogeneous vegetation structure, with groups that are almost even-aged forming an unevenaged structure at a larger scale. 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. In both stands, parts of the living crown frequently reached the ground, irrespective of age. The diameters and heights of the trees in the research area have been measured every ten years since 1990, while the diameter of a subset of trees is measured annually by manual dendrometers (UMS, München, Germany).

**Research questions**

In the context of the interaction of forests and meteorological drivers in conditions of climatic change and, we are aiming a better understanding of the ecohydrology of a subalpine forested catchment. Specifically, we detail also the following three 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?

To answer these questions, we complemented a highly instrumented long-term monitoring site, belonging to the ICOS network, where precipitation, ET through eddy covariance technique and SWC variation at several depths are routinely performed with additional measurements, including water discharge, sap flow, throughfall, fog interception and water holding capacity of lichens.

## MATERIAL AND METHODS

Modelling methods are important for silviculture and land managements. To apply advanced modelling methods, existing studies were considered (Ning et al., 2025; Tuğrul *et al.*, 2025; Bayhan et al., 2025; Lemenkova, 2024c, 2024d; Bai et al., 2025). Mapping was done using Generic Mapping Tools (GMT) software using scripting techniques (Lemenkova, 2022c, 2025b). The inventory (tree height, size, and position) was performed using the TruPulse sensor (series 360 B range-finder; Laser Tech, Centennial CO, USA). In addition, the tree size was assessed using a laser technique involving a UAV-mounted laser scanner flight (Miao *et al.*, 2025). Local spruce and Swiss stone pine were characterised by an almost columnar shape. This shape and the high leaf area index (LAI) (average 5.1, measured by hemispherical image), created peculiar microclimatic conditions within the crown.

***Measurements of water balance***

Measurements of water balance was performed at the catchment level. The water balance at the catchment level can be quantified by the *Equation 1*:

$$ET = P + F + C - D \pm SW - R \quad \text{Eq. 1}$$

Where ET is evapotranspiration, P is Precipitation, F is fog, C is capillarity, D is drainage, SW is soil water content and R is runoff. Here, we considered and quantified all these components except C and D, including the fog, which is frequently neglected in water balance studies. Average values of radiation, relative humidity and vapour pressure deficit (VPD) during days with precipitation, fog and mixed precipitation in 2015 were calculated to predict fog occurrence. The ratio of total to global radiation (ratio Rg dif/Rg tot) was lower during dry periods when total Rg was high. On the contrary, diffuse Rg was less affected by rain and fog. The VPD was higher and relative air humidity (RH) lower during dry periods compared to periods with fog and precipitation. Data variability was higher within the Rg dif/Rg tot ratio than within the RH and VPD.

***Measurements of evapotranspiration (ET)***

Evapotranspiration was assessed by the eddy covariance technique. The measuring system was composed of a 3D ultrasonic anemometer (Gill HS-50, Lymington, UK) and an enclosed-path infrared (IR) gas analyzer (Li 7200 LiCor, Lincoln, NE, USA). The instruments were placed on a tower at 33.7 m above ground level. Air samples were taken through an insulated steel tube of 4 mm in internal diameter and 0.75 m in length at 0.15 m from the anemometer. The airflow rate was set to 12 L $min^{-1}$, as provided by the flow module (7200–101, Li-Cor). All the setups followed the ICOS methodology. 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 software (version 6.2.1).

***Measurements of precipitation (P)***

Precipitation was assessed by a weighing pluviometer Geonor T200x. The periods characterized by dry conditions were compared with periods of wet conditions (fog and with rain). The data included observation (obs) and the prediction (pred) models. The number of days characterized by dry conditions, fog, precipitation (rain or snowfall), and mixed precipitation were calculated. Three representative time periods from late May to early July, from mid- July to early September and from mid-September to early November were selected to study meteorological conditions and precipitation. The pluviometer was installed on a steel basement placed in a forest gap. The data were collected on a CR3000. In parallel, a tipping-bucket pluviometer was installed. The data were collected on CR6 Campbell Scientific datalogger.

All the data were sampled every 20 seconds and averaged at 30-min time steps. Water balance measurements included water discharge in soil and possible percolation.

***Measurements of fog (F)***

The role and contribution of fog were estimated by its impact on throughfall. We first determined an equation between throughfall and precipitation rates for mixed precipitation and rain-only events for both stands, *Equation 2.*

$$P = Pr + Pm + F = Tf + I + Sf \qquad \text{Eq. 2}$$

where P is precipitation, Pr is precipitation from rain, Pm is mixed precipitation, F is fog, Tf is throughfall, I is interception of canopy, and Sf is stemflow. Stemflow was measured at one tree each at the old and young stand. Water running downwards around the tree trunk was collected into a funnel, and measured with a tipping bucket pluviometer. The measured volume of stemflow was divided in the projected crown area of the trees to convert the data into mm. Soil water content was measured continuously within the study site and the change of soil water content was calculated as the difference between the start and end of the measuring period and the hydrologic year, respectively. Water discharge at the catchment scale was measured using a combination of a water stage sensor and flow velocity measurements. The water stage sensor was placed at the lowest spot of the catchment, just above an artificial water basin and continuously measured the height of the water table in the stream (S in cm).

These gave a predicted throughfall for a given precipitation event with rain 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 from precipitation and the slope of the throughfall to precipitation equation from rain-only events.

***Measurements of runoff (R)***

Water discharge at the catchment scale was measured using a combination of a water stage sensor and flow velocity measurements performed with the salt dilution method. The water stage sensor was placed at the lowest spot of the catchment, just above an artificial water basin (46°35′00″N, 11°26′02″E, 1,675 m a.s.l.) and continuously measured the height of the water table in the stream (S in cm). Discharge (DC in l $s^{-1}$) was calculated using *Equation 3:*

$$DC = a \times S^b \qquad \text{Eq. 3}$$

where *a* and *b* are empirical parameters according to the salt method. The continuous water depth measurements were conducted in the creek with an OTT PLS 500 (OTT HydroMet Corp, VA, USA). Stream flow velocity was assessed monthly and in two more instances during 2019 after heavy precipitation events.

***Measurements of tree transpiration (T)***

Tree transpiration was estimated by measuring the sap flow of five spruce trees with a DBH ranging from 23 cm to 57 cm. The sap flow measurements of up to 10 trees going back to 2016 showed a representative behaviour of these trees for their size classes. To minimize errors due to incoming shortwave radiation, one sensor of the tissue heat balance sensor was installed on the north side of the trees. The measuring system provided sap flow rates integrated for the whole sapwood depth per unit trunk circumference (kg $h^{-1}$ $cm^{-1}$). The measured values were logged every 10-min and scaled to the tree level by multiplying with stem circumference (minus the bark and phloem thickness measured during sensor installation) and integrated them to 30-min and daily sums per tree (L $day^{-1}$).

When a sensor was installed for more than a year, we checked whether wound reaction and/or an accumulation of resin led to a decrease in sap flow by comparing the 95$^{th}$ percentile (P95) of 30-min sap flow rates. For the two smallest trees, a considerable decrease in the P95 sap flow was found and consequently corrected sap flow by multiplying it with the ratio of P95. 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 projected crown area was estimated from the mean crown radius measured in the four cardinal directions. The average tree transpiration of the two smaller trees (DBH *23* cm and 32 cm, respectively) was used to represent the young stand, while the average of the three larger trees (DBH 43 *cm,* 50 *cm*, and 57 *cm*) was used to represent the old stand. All selected trees were dominant or codominant.

***Measurements of precipitation (P)***

Precipitation below the canopy as throughfall was measured with sixteen manual rain gauges, arranged in two groups of eight in the two main forest formations, the 200-year-old section and the 30-year-old section. These pluviometers, with a 10-cm diameter orifice, were arranged in rows with a 5-m distance between each pluviometer and data were recorded almost on a weekly basis. Additionally, six tipping bucket pluviometers (with a Hobo data logger; Onset) arranged 5 m apart in two groups of three continuously recorded the below canopy precipitation at a 10-min resolution. To increase their collection representativeness, funnels with a diameter of 30 cm were placed above the orifice of each pluviometer.

***Evaluation of the impact of tree age and epiphytes***

To estimate the lichen weight, the tree was divided into 3-m 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 first wetted until water saturation and then weighed to assess the fresh weight. They were then dried in an oven at 45 °C until a constant weight was achieved and then weighed (Sartorius Entris 2202, Göttingen, Germany) to assess their dry weight

## RESULTS AND DISCUSSION

Evapotranspiration (ET) is another parameter relevant to the understanding of subalpine forest ecohydrology. It presents the partitioning between precipitation (P) and transpiration (T), Figure 3.

The impact of tree age and epiphytes demonstrated clear effects on climate. The role of lichens in the water balance was assessed by measuring air temperature and humidity inside the crown and the water storage capacity of the lichens at two different tree heights. The water storage capacity of the lichens was assessed in spring from a tree falling in the previous winter, with a tree height of 28 m and a DBH of 53 cm which is representative of the old stand.

Several models have been developed to partition ET and these models have been tested across several climates, plant functional types and sites Alpine forests, 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 coniferous forests have a specific combination of temperature and precipitation, Figure 4.

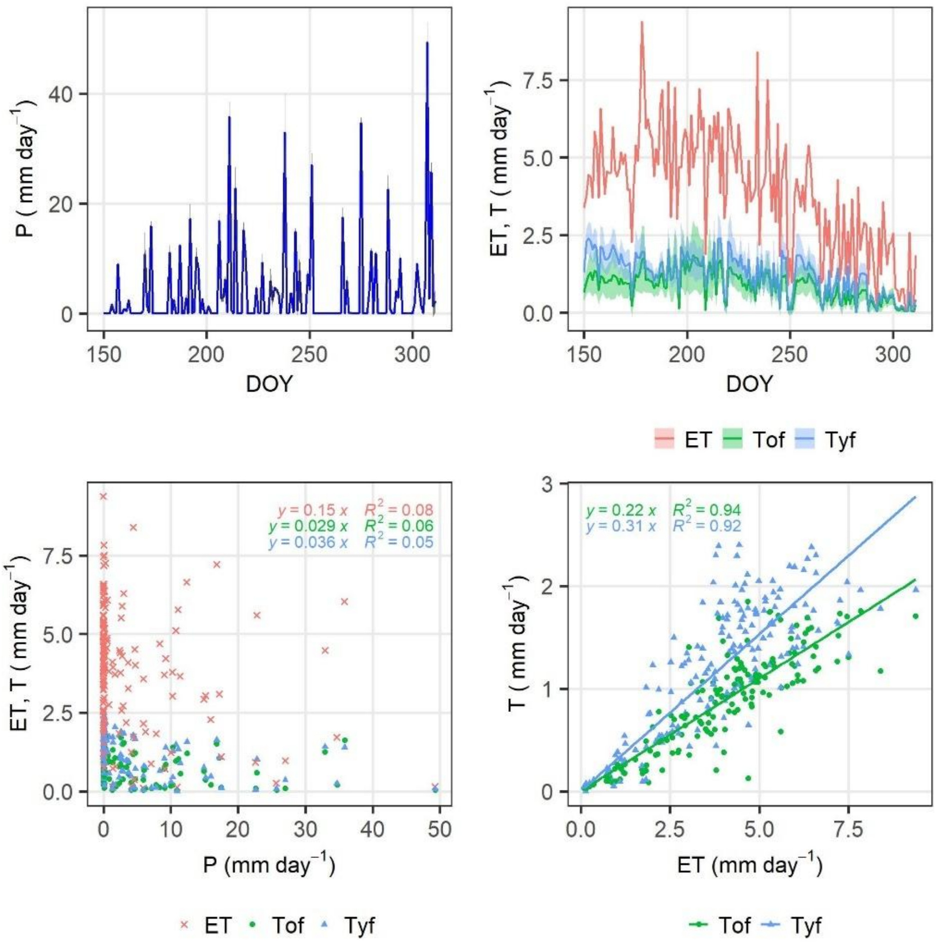


Figure 3. Statistical analysis of the measured dataset: variations of the meteorological parameters (evapotranspiration, temperature and precipitation).

Comparing the obtained results with similar studies, current findings reveal fog as the missing tie to understand not only soil water recharge during days with mixed precipitation but the decrease of evaporative conditions during dry periods in the studied Alpine ecosystem. For example, in tropical and cloud forests, fog represents a relevant component of the annual water input.

Fog may contribute between 0.2–4.0 mm day$^{-1}$ in subtropical and tropical cloud forest environments (Wang *et al.*, 2022; Wu *et al*., 2018). In a tropical rainforest, directly measured maximum liquid water content (LWC) values of approximately 100 mg/m$^3$ in dense fog in Puerto Rico (Holwerda *et al.*, 2006). However, their spectrometer applied a cut-off point of 50 µm; therefore, we the actual LWC value may have been higher. Higher values of 100–500 mg/m$^3$ are observed in Quebec at 850 m a.s.l. and between 100–200 mg/m$^3$ in El Tofo (Chile).

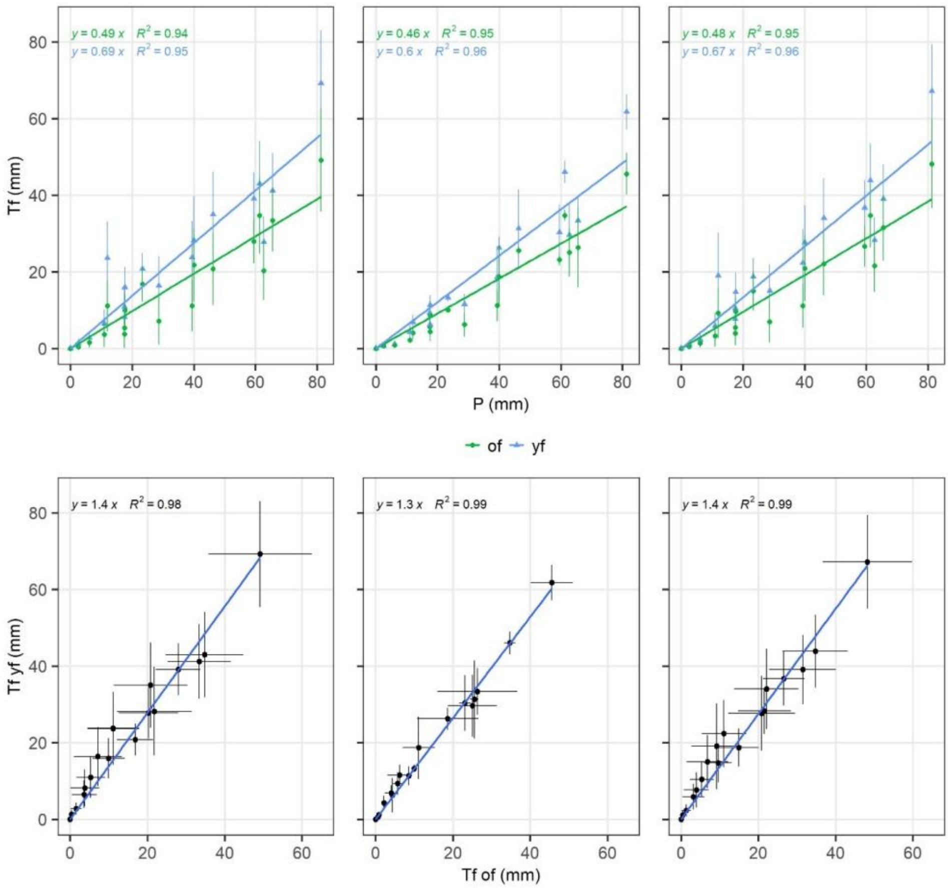


Figure 4**.** Variations of the precipitation and temperature in forest stands

Trunks and branches are larger in the old forest sections, but spruce and pine cork have limited capacity to hold water. Precipitation measured inside and outside the forest (minor amount of precipitation during "dry" period because periods were defined based on the outside climate station alone), throughfall and stemflow measured with automatic tipping gauges, storage/interception calculated as P - Tf – St for young and old forest stands**,** Table 1.

Water components for old (> 200 years old) and young forests (< 30 years old) were evaluated during 5 months from 2019-5-30 until 2019-11-07 at canopy level roughly divided into months according to sampling dates of the manual throughfall gauges. The results are summarised in Table 2.

Table 1. Hydrological components at canopy level.

| Period | nr of days | P | ET | Throughfall | Stemflow | Interception |
|---|---|---|---|---|---|---|
| young forest | | | | | | |
| dry | 78 | 1.3 ± 1.8 | 350.2 | 2.62 ± 3.31 | 0.002 | -1.34 ± 3.28 |
| fog | 8 | 0.1 ± 0.2 | 26.2 | 0.16 ± 0.00 | 0.000 | -0.01 ± 0.16 |
| mixed fog+P | 42 | 459.7 ± 35.2 | 109.6 | 291.86 ± 25.59 | 1.030 | 166.84 ± 35.59 |
| rain/snow | 34 | 132.4 ± 20.9 | 146.8 | 47.03 ± 11 | 0.055 | 85.31 ± 18.97 |
| old forest | | | | | | |
| dry | 78 | 1.3 ± 1.8 | 350.2 | 0.58 ± 0.19 | 0.004 | 0.69 ± 1.41 |
| fog | 8 | 0.1 ± 0.2 | 26.2 | 0.06 ± 0.00 | 0.000 | 0.09 ± 0.17 |
| mixed fog+P | 42 | 459.7 ± 35.2 | 109.6 | 216.49 ± 11.43 | 0.774 | 242.46 ± 29.11 |
| rain/snow | 34 | 132.4 ± 20.9 | 146.8 | 35.67 ± 2.81 | 0.178 | 96.54 ± 16.41 |

Table 2**.** Water components at canopy level 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) | 459.7 ± 35.2 | 459.7 ± 35.2 |
| Total Tf measured (mm) | 291.9 ± 25.6 | 216.5 ± 11.4 |
| Tf estimated from rain only events (mm) | 242.6 ± 6.7 | 184.1 ± 8.2 |
| Fog contribution in mixed events (mm) | 70.3 ± 14.9 | 52.9 ± 4.7 |
| measured 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 |

The combination of high precipitation and low temperature varies, exceeding the combination of T and P depicted by the Whittaker scheme. Based on the energy balance ratio (EBR) values computed monthly, we estimated the systematic errors in the eddy covariance measurements for LE+H to be 17.6%. Given a Bowen ratio of approximately 1 in the summer, this error can be assumed to be half of this value in LE (8.8%) and, therefore also in ET. The random error of EC and the other components of the water balance are calculated statistically. Figure 5 shows the variations of precipitation and temperature according to the measurements with specifics for young and old forest stands. It shows the site with the highest degree of water intercepted by the canopy, promoting a large fraction of wet canopy E.

Water components were measured from 2019-5-30 (DOY 150) until 2019-11-07 (DOY 311) at canopy level based on daily data divided into dry and precipitation periods, Table 1. From a forest management perspective, it would be relevant to understand whether young or old forests, growing in this specific habitat conditions, have a higher water retention capacity. Young forests generally achieve quite early a similar leaf area as mature forests, therefore having a similar water-holding capacity.

Comparing to fog measured in a subtropical cloud forest, those studies accounted for more than half of the precipitation inputs to the upper montane cloud forest (Liu et al., 2021). However, fog measured in a similar cloud forest on Tenerife Island was two times higher (Arévalo *et al.,* 2011). Though the water input through fog-only events at our site remained unknown, fog clearly contributed in mixed fog and rain precipitation when it was estimated to cause additional throughfall compared to rain only events. Also important is that fog was not considered in past studies.

The relevance of fog for the water balance of temperate mountains such as the Alps is still largely 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, compared to other regions, and promoting the occurrence of fog vegetation, is that fog frequently occurs together with liquid precipitation, determining ‘mixed precipitation’ events.

## CONCLUSIONS

Subalpine forests show the abundant cover of epiphytes, bryophytes and particularly lichens. Previous studies assessed their species composition and their interaction with the climate. 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, presumably losing water without high water deficit limitation as the trees do. If relevant, this behaviour would affect the ecosystem response to energy partitioning. The presence of lichens represent an indirect effect of fog occurrence since it is extremely effective in providing water to these organisms, which can make photosynthesis and develop as a direct function of water status.

Since measurements of the water balance components usually involve considerable uncertainties, we used advanced modelling tools to hydrological approach with a case of South Tyrol forest. We also investigated the role of forest in the partitioning of precipitation between water intercepted by canopy and soil and water discharge. Besides, the study investigated the differences between old and young forest formations in the water interception capacity and found the crucial role of epiphytes in this regards. Finally, the differences between old and young forest formations in the water interception capacity were evaluated and statistically analysed, to reveal the role of epiphytes in the canopy water retention capacity. To understand, what are the drivers of water interception and discharge, the statistical analysis was performed using Python modelling tools.

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