MULTITASK LEARNING WITH STATISTICAL PARAMETRIZATION FOR ECOHYDROLOGICAL ANALYSIS

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ABSTRACT

This paper proposes a novel multi-task statistical learning framework which aims to concurrently address all the environmental challenges in the Alps. The goal is to analyse the effects of lichen and fog on water balance. The objective is the analysis of water balance mechanisms by investigating the contribution of fog and the role of forest age in the water cycle. The methods include advanced multitask learning with statistical modelling techniques. The results shown that interception plays a dominant role in the precipitation and evapotranspiration partitioning, enhanced by lichens. Trees transpiration as lower in the young stand and the evapotranspiration of soil and understory contributed considerably to the water balance at both stands. Moreover, fog caused additional throughfall in mixed fog and rain precipitation.

RÉSUMÉ: Apprentissage multitâche avec paramétrisation statistique pour une analyse écohydrologique.

Cette étude examine les effets des lichens et du brouillard sur le bilan hydrique des Alpes. L'objectif est l'analyse des mécanismes du bilan hydrique: contribution du brouillard et rôle de l'âge de la forêt dans le cycle de l'eau. Les méthodes incluent un apprentissage multitâche avancé avec des techniques de modélisation statistique. Les résultats montrent que l'interception joue un rôle dans la précipitation et l'évapotranspiration, renforcée par de lichens. La transpiration des arbres était plus faible dans le peuplement jeune, tandis que l'évapotranspiration du sol et du sous-bois a contribué considérablement au bilan hydrique des deux peuplements.

REZUMAT: Învățare multisarcină cu parametrizare statistică pentru o analiză ecohidrologică.

Acest studiu investighează efectele lichenilor și a ceții asupra echilibrului apei din Alpii. Obiectivul este analiza mecanismelor de bilanț al apei: contribuția ceții și rolul vârstei pădurilor în ciclul apei. Metodele includ învățare multisarcină avansată cu tehnici de modelare statistică. Rezultatele au arătat că interceptarea joacă un rol în compartimentarea precipitațiilor și evapotranspirației, sporită de licheni. Transpirația arborilor a fost mai scăzută în arboretul tânăr, iar evapotranspirația solului și a tufărișurilor a contribuit considerabil la echilibrul hidric la ambele arborete. Ceața a provocat căderi suplimentare de precipitații mixte de ceață și ploaie.

INTRODUCTION

Background

Subalpine forests are fragile ecosystems with high importance for human water resources as well as local and mesoscale climate (Montané et al., 2016; Wong et al., 2010). The Alps represent an essential source of water availability in Europe (Kruse and Pütz, 2014; Wieser, 2010), a role expected to become even more crucial under climate change conditions. Vegetation interacts profoundly with the water cycle, influencing both water availability for human needs and the distribution between sensible heat and latent heat, therefore interacting with the radiative forcing feedback mechanism (Wang et al., 2012; Jiang et al., 2004). For instance, in mountain regions, the primary cause of land desertification and land cover change is degradation of vegetation (Dregne, 2002; Hill et al., 1995). In turn, one of the main causes of vegetation deterioration is water stress (Borgogno et al., 2010; Xia et al., 2009).

The water cycle mechanisms in the Alps are inextricably linked to the water required for vegetation development. Mountain regions are essential sources of water which impact extending far wider than their actual range (Beniston et al., 2011; Viviroli et al., 2007; Messerli et al., 2004). However, they are also strongly affected by climate change with past and projected warming exceeding the global average (Gobiet et al., 2014; Beniston, 2005). Besides, subalpine forests in mountains are ecologically significant due to their unique biodiversity and vulnerability to climate change (Zhang and Wang, 2023). While previous studies have measured different components of the water balance (Netherer et al. 2019), little is known about the frequency and influence of fog and the role of forest age in the water balance.

The distribution of vegetation of mountain regions is largely driven by the change of climate and soil conditions along elevation gradients (Grabherr et al. 2010; Nagy, 2006). Besides, the pattern of vegetation is also influenced by the complex (micro-) topography (Körner, 1998), which is an important, but often neglected factor in the mountain water balance. In alpine environments, topography has a significant impact on vegetation distribution patterns, vegetation activity, and hydro-climatic dynamics (Li et al., 2025). For instance, the temperature and precipitation along elevational gradient have dominant effects on the subalpine vegetation activities with alternating strength (Kakarla et al., 2025). Mountain forests have a high capacity to influence the water balance by intercepting water through the canopy and releasing it back to the atmosphere as vapour, which keeps the water cycle running (Proutsos et al., 2025).

Water retention functions makes forest ecosystem to be one of the major regulators of the climate (Chen et al., 2025). This is hence its principal ecological role enabling to preserve the natural water balance in subalpine environment. Additionally, mountain forests reduce runoff and increase infiltration (Yu et al., 2025). Consequently, vegetation density increases in water yield and clear cutting, while in contrast, is increasing risk of higher runoff (Fines et al., 2023). The cumulative effects of climate changes (precipitation) with forest degradation would therefore have consequences on the ecohydrological status of subalpine environments. In the Alps and other Central European mountains, the subalpine elevation belt is mostly covered by forests dominated by temperate conifers (Bohn et al., 2000). Of these, the eastern part of the Alps is particularly humid and is dominated by spruce forests. In the study area, spruce forests cover 178,000 ha, which is 52.8% of all the forests in the region, which is covered by forests on 45.7% of its surface (APBS, 2022). However, they are also strongly affected by climate change with past and forecasted processes of warming exceeding global average (Augustaitis and Pivoras, 2024).

Warmer air temperatures may have very distinct consequences for alpine forests, such as an increase in radial growth, which may depend on sufficient water availability to compensate for the increased evapotranspiration (ET) (Vittoz et al., 2008). The increase of air temperature and vapour pressure deficit (VPD) leads to forests being losing more and more water through the process of evapotranspiration. Thus, moisture availability needs to be considered to predict the consequences of future climate change. Forest overuse, changed patterns of land use types, clear cutting, and local land degradation can lead to diverse environmental problems, such as soil erosion, landslides, rockfalls, increased water runoff or reduced water storage. Other effects include, for instance, the drying of springs and wetlands, and biodiversity loss, and have severe impacts on livelihoods or even cause human deaths (FAO, 1998). However, there are still gaps in the understanding of water redistribution in forests and its consequences for land-use management, water policies, and the climate system. In this paper, we contribute to fill in some of these gaps through analysis of water balance mechanisms, specifically by investigating the contribution of fog and the role of forest age in the water cycle.

Objective and goals

Despite the importance of the interaction between forests and regional hydrology, few studies have determined the various components of the water cycle and evapotranspiration partitioning at the basin level on forested terrain (Castelli et al., 2018). At the same time, evapotranspiration process and its contribution by forests at the basin level is crucial for a thorough understanding of energy, water, and carbon cycles in mountain forest ecosystems (Zweifel et al., 2010). In particular, given the high cloud cover characterizing the Alpine mountains (Chen et al., 2022), the question is what the direct contribution of fog water might be to the hydrological cycle. Montane forests support formation of wind-driven clouds and fog, providing crucial moisture to the ecosystems (Reger et al. 2011). Besides, this study explores whether fog might indirectly contribute to ecosystem water availability. The formation of fog favours unique environments that host a wide variety of specific lichens and plants. In turn, lichens can influence the water cycle due to their inherent water retention capacity.

Measurements of the water balance components are usually surrounded by considerable uncertainties. Meanwhile, the numerical assessment of water balance components is crucial for sustainable management of water basin and analysis of water cycle in mountains (Bredemeier, 2011; L’Vovich, 1979). Such components have been affected by climate change in subalpine environment over the recent years (Tscholl et al., 2025). In hydrological approaches, water balance is widely based on simplifications and model generalizations (Buri et al., 2023). Existing experimental studies where the different components of the water cycle are directly measured are scarce. In the context of the interaction of forests and meteorological drivers in conditions of climatic change, this study aims at better understanding of the mechanisms of ecohydrology of a subalpine forested catchment.

Frequently, one or more of the components of the balance are assessed indirectly, with a modelling approach. The same happens concerning flux partition techniques (Sánchez-Carrillo et al., 2001). Meanwhile, major atmospheric boundary fluxes: evapotranspiration (evaporation and transpiration) and irrigation and the lower boundary fluxes such as soil percolation are essential elements of water balance and environmental sustainability of mountainous forests (Chen et al., 2024; Idrees et al., 2022).

In this general context is required the study of the mechanisms of their functions within water cycle.

Fraction of water transpired by the vegetation

The evapotranspiration (ET) partitioning between evaporation (E) and transpiration (T) is a fundamental topic relevant to the understanding of subalpine forest ecohydrology (Jin et al., 2025). Recently, several models have been developed to partition ET and these models have been tested across several climates, plant functional types and sites (Fang et al., 2016; Lujano et al., 2016; Koliopanos et al., 2025). The ecosystems of Alpine forests, however, have a specific input in the maintenance and regulation of the forest water cycle, by collecting and filtering large amounts of water: 1. 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 in sparse broadleaved forests like woody savanna; 2. 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 precipitation (P) depicted by the Sharma et al. (2016).

In ecohydrology, the partitioning is resolved by separating evapotranspiration into evaporation from surfaces inside the forest and transpiration by the vegetation (Mastrotheodoros et al., 2020; Savenije, 2004). While tree transpiration and soil evaporation can be measured directly through sapflow sensors (e.g., using canopy chambers), evaporation from canopy interception can be estimated indirectly or through modelling and simulation techniques; thus, there are still uncertainties to be solved. For example, concerning the rate of wet canopy evaporation estimated from eddy covariance measurements or as the differences between precipitation, throughfall and stemflow, or those using the conventional Penman-Monteith-equation by a factor of two or more (Holde and Gibbes, 2016; Holwerda et al., 2012).

The amount of water intercepted by the forest canopy varies with its age, structure and leaf type (Leng et al., 2025). Depending on the stand characteristics, for instance, hardwood, coniferous, lichen woodland, and closed-canopy forests, forest type is a major predictor of canopy interception rates (Cau et al., 2025; Huang et al., 2025). Nevertheless, important features are the occurrence of mosses and epiphytes which may intercept high amounts of water (Bruijnzeel and Proctor, 1995). They store water inside the forest, sustain evapotranspiration, decrease the Bowen ratio, and increase the air humidity (Pokpongmongkol et al., 2025). In this way, rain and cloud forests maintain minimised (almost zero) water pressure deficit conditions and pose little water stress to leaves, and particularly to epiphytes. This could also be the case for temperate mountain forests, where needles can live for years and epiphytes develop on boles and branches of old trees.

Study area

Subalpine forests, frequently show an abundant cover of epiphytes, bryophytes, and particularly lichens (Rixen et al., 2007; Narukawa et al., 2003). The distribution of lichens in spruce-fir forests is influenced by vertical position within the canopy which in turn contributes to water balance. Their species composition is influenced by climate. However, there is scarce information 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. For example, the diurnal cycle of evapotranspiration partitioning in subalpine cloud forest with lichens would differ from the one in subalpine cloud forest through higher relative humidity (Wen et al., 2022). Such behaviour would affect the ecosystem response to energy partitioning. The presence of lichens can therefore represent an indirect effect of fog occurrence as it is effective in providing water to these organisms, which makes photosynthesis and develop as a function of their water status (Villegas et al., 2008).

Lichen epiphytes play significant ecological role as an important biological category in forest habitats of Alps (España-Puccini et al., 2024). Epiphytic lichens are extremely reliant on the traits of their host trees, especially the bark (Lyssaios et al., 2025). The distribution of lichens varies according to available habitats and forest composition and maturity (Tumur et al., 2025). In aged forests, lichens continue to grow on old plants and increase interception capacity, when the stand leaf area index has already reached its maximum (Rodríguez-de la Cruz et al., 2025). Highly diverse in species and genera, they increase canopy interception of precipitation and absorb some essential components from the air and fog, which they then release through leaching or decomposition (Belinchón et al., 2007). These processes significantly contribute to the cycling of water and nutrients (Palmqvist et al., 2017).

Alpine mountain forests may be characterized by high cloudiness, as measured by Castelli et al. (2018) using satellite data. However, the amount of fog water available for the water cycle in the mountain forest may be substantially different from that in rain forests and cloud forests in the tropics. We hypothesise that fog may have a minimal impact on the annual and seasonal water budget, also observed in subtropical cloud forests. However, most importantly, we do not know how much moisture, may bring to the canopy structures. The vegetation groups are even-aged forming an uneven aged 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, indicating the closed-canopy forest type, irrespective of age.

MATERIAL AND METHODS

The methods include advanced multitask learning with statistical modelling techniques. The technical approaches include monitoring by the eddy covariance technique, tree transpiration sensors, phenocam images, throughfall and stemflow gauges, water discharge measurements, soil moisture sensors and epiphytes quantification for young and old forests (Fig. 1). 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. In this study, we employed two different methods, the eddy covariance for measuring total evapotranspiration, and sap flow sensors to examine the variability of the transpiration levels. Additional measurements at the soil level were performed in an old and young forest, in which we measured soil moisture (Fig. 1). Water discharge was measured at the catchment level. 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 high variability in the composition of plant communities. To highlight the unique nature of meteorological conditions during dry and wet conditions, we analysed the robust techniques to measure meteorological variables in 2015 and 2019. Here, we evaluated the data 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 characterise 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.

Figure 1: Position of the measurements using laser techniques.

The relation between precipitation type and these three meteorological drivers were then used to predict the occurrence of fog and mixed precipitation during the study period 2019. These predictions were compared to fog observations from a public webcam located at three km and 300 m lower in elevation than the study site. The water partitioning at the catchment level was estimated for the old and young stand (old forest-of and young forest-yf, respectively) for five months during the growing season of 2019. The periods of dry conditions were compared, with fog and with rain, using data for 2015 and 2019, by including both the observation (obs.) and the prediction (pred.) periods to assess the accuracy of the predictions.

The number of days characterized by dry conditions, fog, precipitation, and mixed precipitation for 2015 and 2019, were calculated and discussed. Three representative time periods from late May to early July, from mid-July to early September and from mid-September to early November during 2019 were selected to study meteorological conditions. Additionally, the supplementary information was used: global radiation: 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, during dry, fog and precipitation periods as well as times with mismatches between the observed and predicted fog.

In this respect, positive feedback might be established between the tree age and evaporation fluxes. To estimate fog water and to determine the methodological applicability of the workflow, the fog was derived from the comparison of the gross and net precipitation. To better understand fog occurrence under changed external circumstances, we compared the relevance of the measured meteorological conditions during three periods: with dry conditions (dry), fog (less than one km visibility) and rainfall. Measured meteorological conditions included the following parameters: relative humidity, temperature, radiation, wind speed and direction, ratio of diffuse to total global radiation and vapour pressure deficit.

RESULTS AND DISCUSSION

The average monthly precipitation, represented as a monthly sum and maximum daily sum, showed the importance of convective rainfall events in the warm summer, while the cold winters were comparatively dry (Fig. 2).

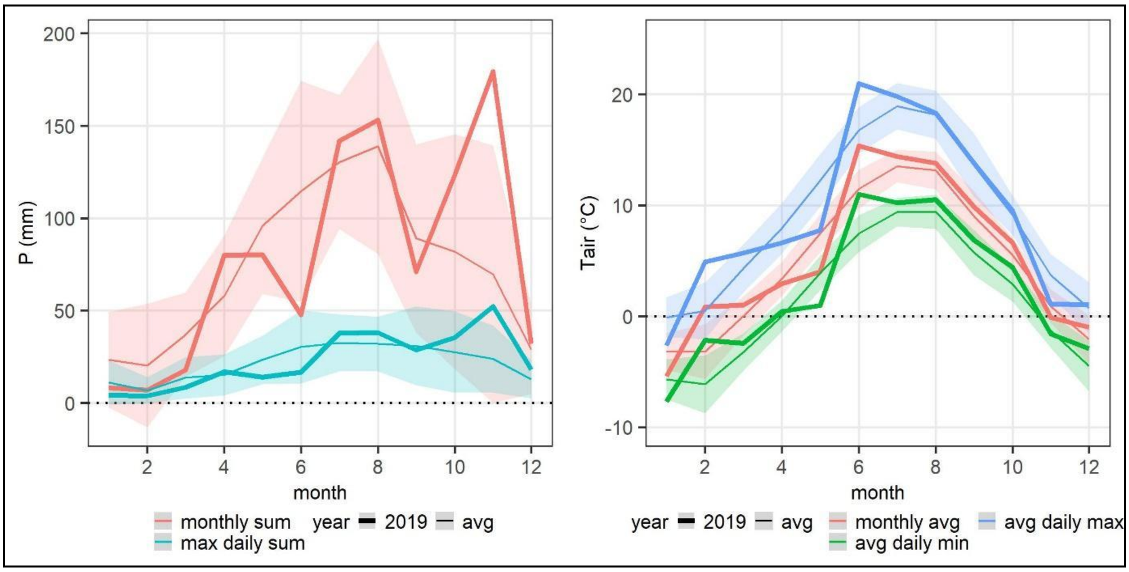


Figure 2: Average monthly precipitation (monthly sum and maximum daily sum) and temperature (monthly average and average daily maximum and minimum) for 2019 (thick line) and for the period from 1999-2019).

The obtained results highlight the importance of days having both fog and rainfall (mixed precipitation). Wagner and Petitta (2015) recorded observations over 254 days with cloudy conditions (70%) in 2011, but did not obtain fog or mixed precipitation data. Unfortunately, further characteristics like cloud thickness, droplet size, and the liquid water content of fog as well as how many of these days were foggy (< one km visibility) were not observed. These are important features useful to assess the importance of fog in the water balance (Frumau et al., 2006). If we consider data from 2019, days with fog (defined as days with fog and days with mixed precipitation) may account for 45% of cloudy days in 2011 (Wagner and Petitta, 2015).

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 in 2019 (visualized in box plot on figure 3). Here, the meteorological conditions (ratio of diffuse to total global radiation, VPD, and relative air humidity (RH) are indicated during periods with fog (less than one km visibility), precipitation, and dry conditions (dry) from January 1st until August 30th 2015 (top row) and from May 25th until August 30th 2015 (bottom row). 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. As expected, VPD was higher and relative air humidity (RH) lower during periods with dry conditions compared to periods with fog and precipitation. Data variability was higher within the Rg dif/Rg tot ratio than within the RH and VPD.

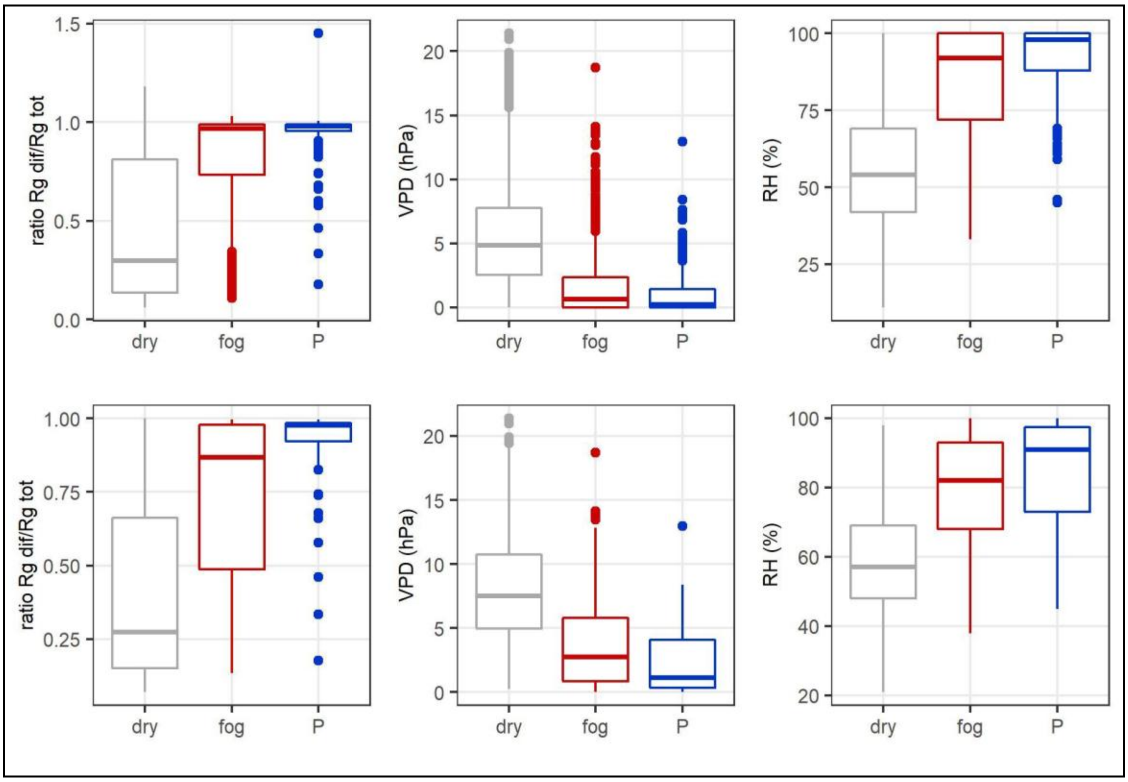


Figure 3: Box plot diagram showing the statistical evaluation of the meteorological parameters (ratio of diffuse to total global radiation, VPD, and relative air humidity, RH) during periods with fog in 2015.

In 2019, the precipitation in the study area was generally in accordance with the 20-year average, except for a drier June, October, and November, which were 1.5- and more than 3-fold, respectively, wetter than the average. These aberrations were also obvious in the maximum daily precipitation. In fact, an exceptional snowfall event starting on 8th November, producing a considerable snow break especially in the young forest, effectively ended measuring season. Likewise, air temperature deviated from the 20-year average in 2019, mainly during the first half of the year: February and June were too warm and May was too cold.

Looking at time courses, air temperature (T) and VPD were overall lower during foggy and wet days and increased during the first dry days, but decreased again towards the end of the measuring period (Fig. 4). More specifically, the graph shows the 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.). The relative humidity exhibited the opposite pattern of T and VPD. According to Vautard et al. (2009), who observed a decrease in temperature during the day but an increase during the night due to fog in long-term data in Europe, a different night-time sensitivity of temperature is expected.

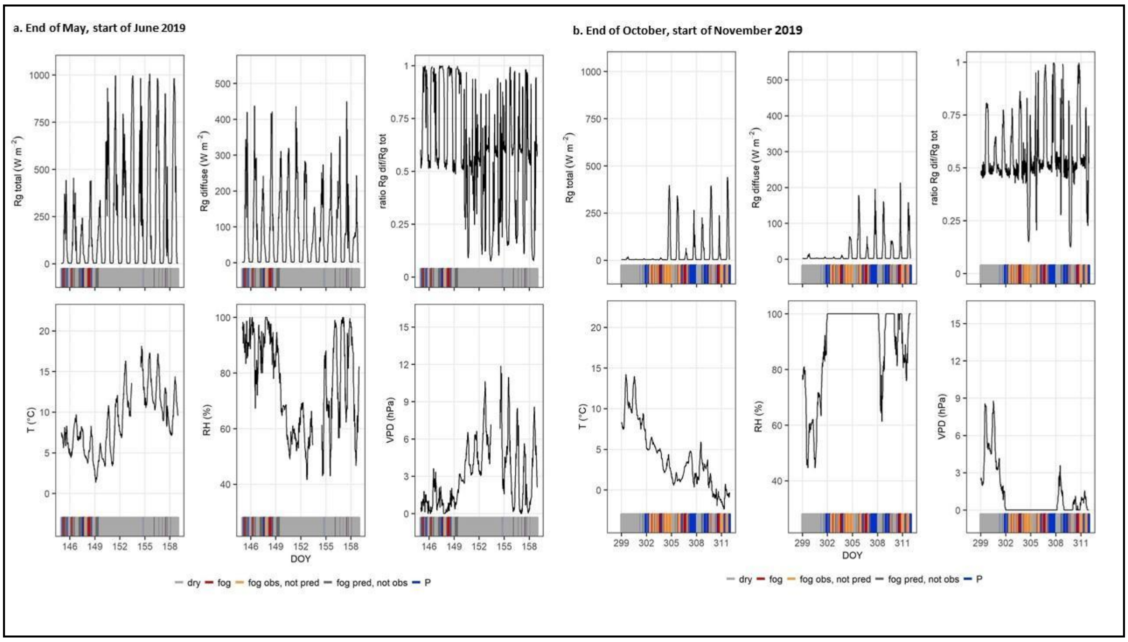


Figure 4: Temporal variations of of global radiation, air temperature, air humidity, and VPD during a foggy period.

Canopy evapotranspiration (ET) is the total flow of water vapour from canopy into the atmosphere, mainly including the processes of transpiration and soil evaporation. Even though the precipitation totals in June 2019 were below the long-term average, rainfall events occurred quite regularly during the entire measuring period of 2019, with only one 5-day dry period at the end of June and another 13 days in mid-September (Fig. 5).

The transpiration of the old (Tof) and young stand (Tyf) calculated from sap flow measurements was low compared to canopy evapotranspiration from eddy covariance measurements, which was applicable to both stands; however, time courses of T and ET corresponded well with similar reactions to weather conditions and an overall decrease starting in the second half of September. Surprisingly, Tyf was higher than Tof, as a smaller projected crown area and higher tree density in the young stand more than compensated for the higher sap flow of large single trees in the old stand. Consequently, the regression line of Tyf to ET had a higher slope than that of Tof to ET, for both forest types. The R^2 of the correlation of T and ET was higher than 0.9. In contrast, neither ET nor T correlated with P.

By splitting the days into dry, mixed precipitation (fog and precipitation), and with rainfall-only, we found that, not surprisingly, ET was higher during dry days (55% of total ET in 48% of days) and was suppressed especially in days characterized by the presence of mixed precipitation (17% of total ET in 26% of days). This could be an effect of fog suppressing ET as observed in cloud forests, but also because days with mixed precipitation occurred more often in autumn when ET was generally lower because of both lower temperature and phenology (senesced grasses). The periods of mixed precipitation during summer should be further investigated.

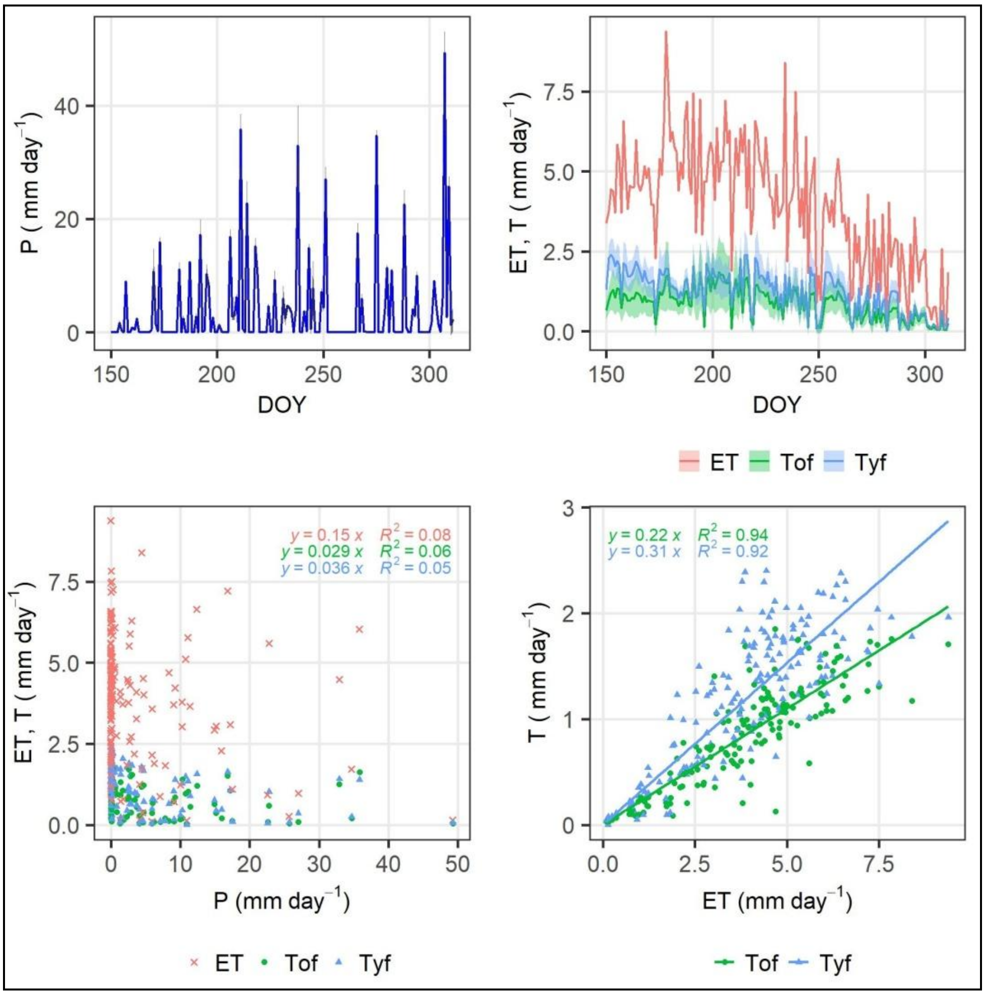
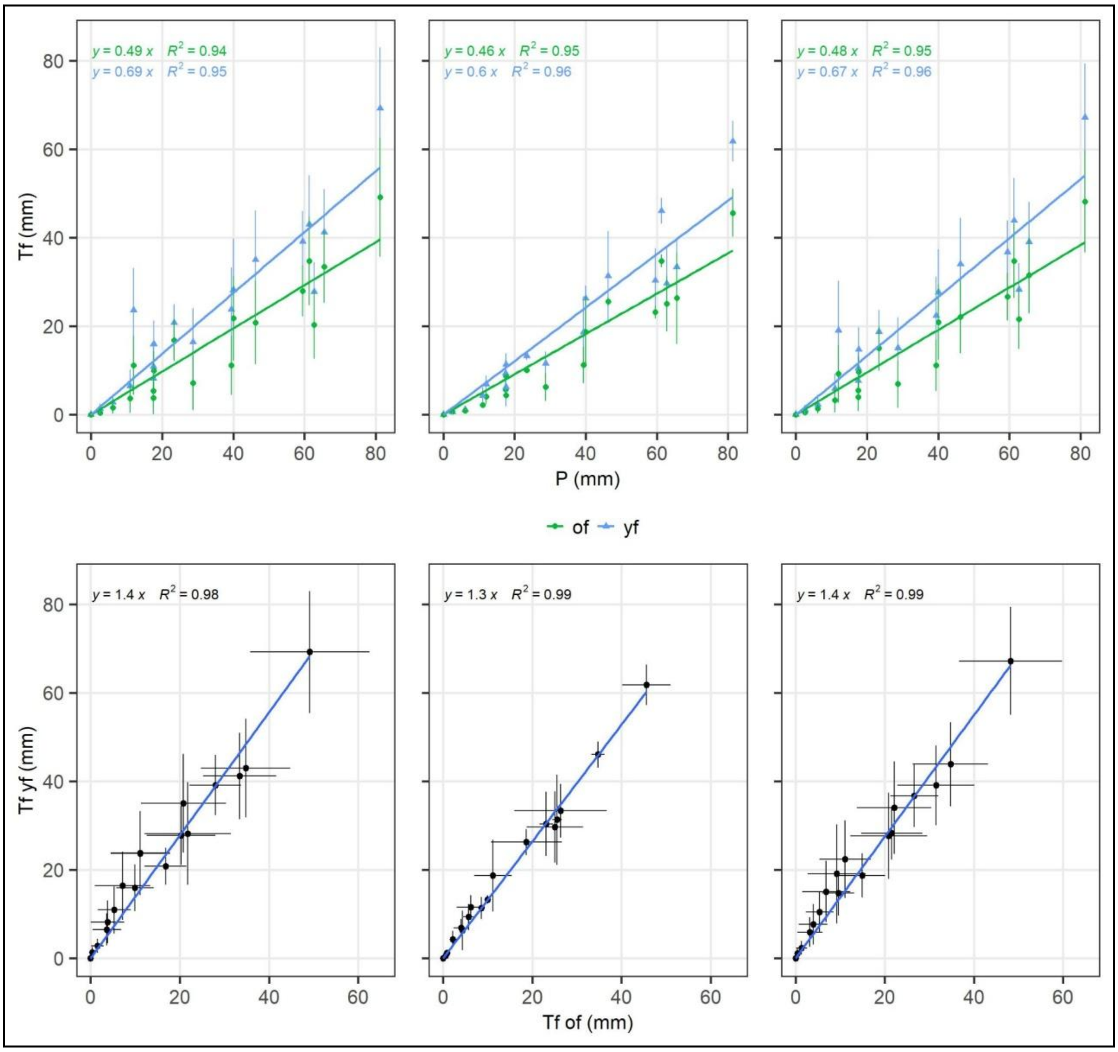


Figure 5: Above: Time course of daily precipitation (P, top left in continuous line for clarity) as well as daily evapotranspiration measured with eddy covariance (ET) and daily transpiration for the old (Tof) and young (Tyf) forest upscaled from sap flow measurements (top right). Below: Correlation of daily ET, Tof, and Tyf with daily P (bottom left) and correlation of daily Tof and Tyf with daily ET.

Water components from 2019-5-30 (DOY 150) until 2019-11-07 (DOY 311) are studied at canopy level. The calculations were based on daily data divided into dry and precipitation periods. The precipitation was 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. The throughfall in old (of) and young (yf) stand versus precipitation accumulated to sampling dates of the manual gauges is shown in figures 6a, b. The values were 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.



Figures 6a, b: The throughfall in old (of) and young (yf) stand against precipitation accumulated to sampling dates of the manual gauges.

In this research throughfall rates relative to precipitation were higher in the young than in the old stand (Fig. 6a) even though the LAI in both stands was similar. Throughfall is the important part of the gross precipitation that passes through the tree canopy and reaches the soil. We detected that throughfall variability was higher in the manual gauges than in the automatic ones as they covered a higher small-scale variability of Plant Area Index (PAI)/LAI (Fig. 6a). 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 (Fig. 6b).

By looking at throughfall rates at a daily resolution and separating by precipitation type, we found that throughfall was much higher during days with mixed fog and rain precipitation (Fig. 7). This surplus in Tf (Tf/P = 0.28 for the young stand and Tf/P = 0.27 for the old stand), was attributed to fog. The throughfall was captured during days with fog-only. This parameter differs in diverse geographical areas significantly. For instance, in subtropical cloud forests with a high frequency of fog, fog-only contributed with only 6% of throughfall (Holder, 2004). This contrasts to the Japanese Alps, Mt. Tateyama, where Uehara and Kume (2012) measured up to 35% of fog-only contribution in throughfall, attributed to the high wind velocity and humidity in the Japan Alps. The lower contribution in the Alpine forest may be explained by differences in air temperature and altitude. This result is in line with the hypothesis that fog might have a minimal impact on the annual and seasonal water budget.

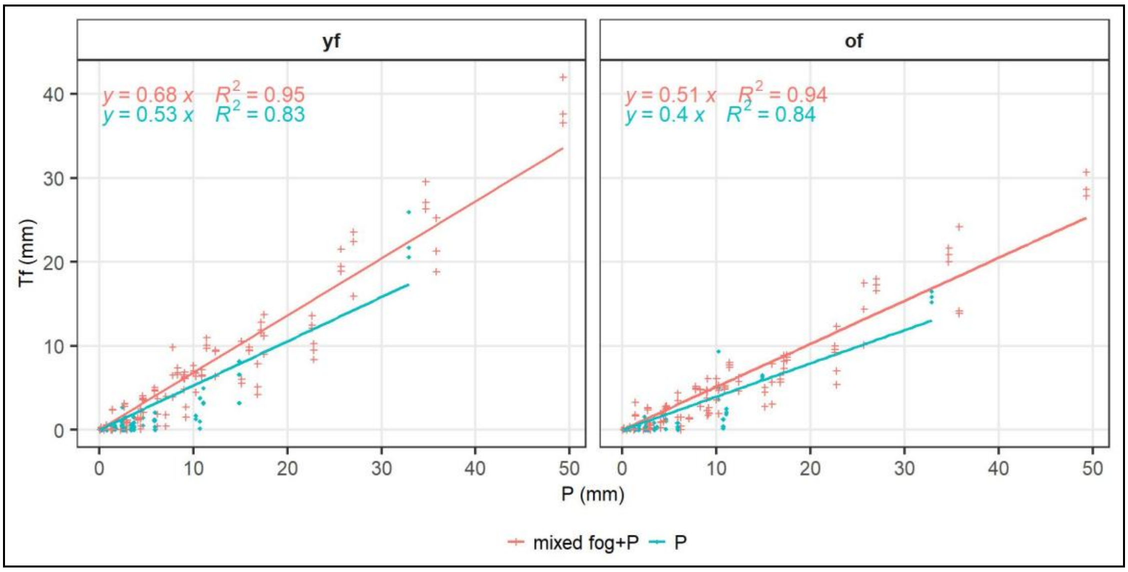


Figure 7: Throughfall versus precipitation during mixed precipitation (mixed fog+P) and rain-only (P) events in the young (yf) and old (of) forest.

By looking at the same water components, split into approximately monthly periods, it can be noticed 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 summer, except for June in the old stand; correspondingly, the interception rate (I/P) was lower. This should be associated with higher P, and with more mixed precipitation days observed in autumn. Water components for five months were estimated from 2019-5-30 (DOY 150) until 2019-11-07 at canopy level roughly divided into months according to sampling dates of the manual throughfall gauges.

To characterise the growing conditions for lichens, we measured some meteorological variables inside the forest. As expected, the relative humidity was higher within the forest, especially at 15 m, where VPD was lowest. Surprisingly, 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 included daily and seasonal variability, and were the highest within the canopy at 23 m. Therefore, the presence of lichens is likely more related to humidity than to temperature.

When accounting for the interception, tree transpiration contributed slightly less to ET than the soil and understory E(T), while Köstner et al. (1998) mention a contribution of the understory that accounts for 10-70% of the total transpiration. Uncertainties regarding the ability of sap flow measurements to measure and predict absolute values could have played a role and led to an underestimation of tree transpiration, as mentioned literature (Flo et al., 2019; Schlesinger and Jasechko, 2014; Wilson et al., 2001). Possibilities for in situ calibration and realistic estimation of measurement errors are still open for examination in sap flow research, even though steps are taken in this direction (Peters et al., 2018).

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

The abundance of lichens in the old but not in the young stand could be a main reason for lower throughfall rates indicating a higher interception capacity in the old stand, even though LAI was similar in both stands. Due to their protected status, we did not conduct a survey on lichens, but we collected them from one fallen tree typical for 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 at 22 m above the soil (at approximately 3/4 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 2/3 of that water again within two days when air-dried.

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. Burgess and Dawson (2004) showed that part of this water and fog can be directly absorbed by the plant through its leaves.

The results confirm the positive feedback loop involving hydrological and vegetation components, which were particularly effective in the old stand due to its higher capacity to store water in its canopy. This was also observed by Sillett and Van Pelt (2007) in an old-growth redwood forest. In addition, it is known that epiphytes survive where humid conditions are guaranteed. Therefore, fog may link the positive feedback loop between the presence of lichens in old-growth forests and cool and humid meteorological conditions.

DISCUSSION

In this study, we quantified the capacity of the forest to intercept water in the canopy, and we provided an estimate of this capacity in the two different forest stands, a 200-year-old and a young, 30-year-old stand. 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 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 (Burgess and Dawson, 2004)

In other regions, for instance, in tropical and cloud forests, fog represents a relevant component of the annual water input (Fu et al., 2016; Bruijnzeel et al., 2011). Fog may contribute between 0.2-4.0 mm day^{-1} in subtropical and tropical cloud forest environments (Bruijnzeel and Proctor, 1995). In a tropical rainforest, Holwerda et al. (2006) reported directly measured maximum Liquid Water Content (LWC) values of approximately 100 mg/m^3 in dense fog in Puerto Rico. However, their spectrometer applied a cut-off point of 50 µm; therefore, we cannot overlook that the actual LWC value may have been higher. Higher values of 100-500 mg/m^3 have been observed in Quebec at an altitude of 850 m a.s.l. and between 100 mg/m^3 and 200 mg/m^3 in El Tofo (Chile). Measured fog in a subtropical cloud forest; according to their measurements, fog accounted for more than half of the precipitation inputs to the upper montane cloud forest on La Gomera Island (594 mm of fog against 900 mm of precipitation). However, fog measured in a similar cloud forest on Tenerife Island was two times higher (1,214 ± 86 mm year^{-1}).

We noticed some differences in the ecosystem water partitioning at the basin level for the 5-months measuring period, between the young and old stand (Fig. 8).

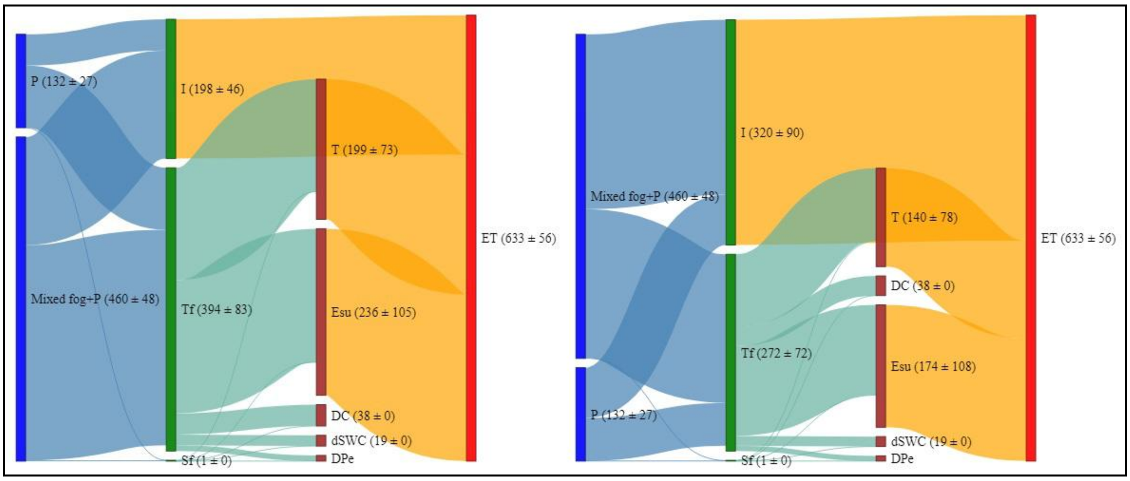


Figure 8: Water partitioning for the young forest (left) and the old forest (right) for the five months measuring period from 30.05.2019 until 11.07.2019.

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.

Throughfall and transpiration were higher in young forest. Consequently, interception which was calculated as the residual of total P minus Tf minus Sf was lower in the young stand. As intercepted water evaporates back to the atmosphere, interception accounted for a major part of ET (54% in the old forest and 33% in the young forest). Evaporation is a part of the water cycle and provides a shortcut for precipitation water to return to the atmosphere without having to pass through the soil or the living parts of plants. This partially explains the low transpiration/ET ratios mentioned earlier. 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 canopy chambers could provide additional information.

Though the water input through fog-only events at the site remained unknown, fog clearly contributed in mixed fog and rain precipitation when it was estimated to cause 24% of additional throughfall compared to rain only events. Also important, fog was not considered in past studies. Findings reveal fog as a missing tie to model soil water recharge during days with mixed precipitation and the decrease of evaporative conditions during dry periods in the Alpine ecosystem.

Apart from the physiological aspect of water use by the plant, the capacity of the intercepted water to act as a climate regulator at a local scale and the mesoscale is climatologically relevant. One mm of water at 20°C represents 44.2 W m^{-2} of latent heat, which is emitted in place of sensible heat, thereby reducing the temperature and increasing the availability of water vapour in the air. The role of fog is mainly to sustain this positive feedback in the water cycle, favouring the presence of dense vegetation and lichens, and increasing the availability of water vapour.

As there is a reduction of water vapour in the air with possible future disruption of the positive feedback 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 (Alkama and Cescatti, 2016). The results demonstrated that fog plays an important role in the water balance. Fog water collection is crucial for water supplies, maintaining surface water in the conditions of climate warming and groundwater. This is especially notable for the periods based on the observation during numerous days with mixed precipitation, maintaining for several days a high relative humidity inside the dense coniferous crowns composing the forest.

CONCLUSIONS

In this study, the frequency of fog events in a subalpine coniferous forest in the Italian Alps was quantified statistically and assessed the hydrological balance at basin and canopy scales by combining different measurement approaches. The difference between water input in rain and snow forms (fog not included) and water output as evapotranspiration and water discharge, plus the variation in the soil water content, was 25 mm, within the uncertainty range of the measurements. Though fog has not been included in past water balance studies, the study revealed that fog combined with rainfall the same day, as mixed precipitation, contributed to higher throughfall, which in turn contributes to higher net precipitation (soil water recharge, in absence of runoff) and evaporative conditions inside the canopy.

Fog water helps the trees to maintain a large amount of leaf area, and the filamentous lichens to grow in the upper canopy. These two features led to a large capacity of the crown, mostly in the mature coniferous forest, to intercept liquid precipitation, release only a small amount of precipitation to the soil and eventually to runoff. These processes contribute to the sustaining of local ET with an associated reduction of the sensible heat flux. Still, the accurate estimation of the amount of fog which was intercepted by the canopy is a future direction.

From a hydrological perspective, this research complements recent evidence which indicates that natural forests play a key role in dampening heat extremes above the vegetated terrestrial ecosystems (Duveiller et al., 2020; Peterson et al., 2012; Alkama and Cescatti, 2016). It also attributes to fog and cloudiness the role of linkage in the positive feedback between the presence of forests (Duveiller et al., 2021) and cool and humid meteorological conditions. Since there are few studies dealing with the contribution of fog and lichens to the water balance of mountain forest in subalpine areas, this work has contributed to filling in this gap with a case of north Italian region.

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