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THE RELATION AMONG SOIL CONDITIONS, LICHEN GROWTH AND PRECIPITATION UNDER SUBALPINE CONIFEROUS FOREST IN NORTH ITALY

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Abstract: Boreal coniferous mountain forests mitigate climate through biophysical and biochemical processes, especially water balance. The link between forests and climate includes direct and nonlinear interactions with atmospheric composition, hydrologic cycle, and water balance. At the same time, forests are fragile ecosystems with high importance as water sources and climate at local and regional levels. Monitoring forest enables to predict consequences of climate change. In this study, the boreal forests were investigated to simulate climate cooling and warming. The area is located in the subalpine mountain forests of South Tyrol. Methods include statistical investigation, eddy covariance assessment of evapotranspiration, water discharge and fog interception. The dense, old-growth forest (>200 years old) was compared in sections with young patches (<30 y. o). Technical instruments included tree transpiration sensors, phenocam images, throughfall and stemflow gauges, water discharge measurements, soil moisture sensors and epiphytes quantification. Despite the importance of coniferous forests, the effect of boreal forests on climate processes is not sufficiently studied. While previous studies measured different components of the water balance, little is known about the frequency and influence of fog in water balance. To fill in this gap, this study presented the investigation on the relationships between water balance, forest age and structure in the Alps of north Italy.

Keywords: coniferous forests, ecology, parametrization, modelling, biosphere, canopy interception, fog

1. Introduction

Climate change affects forest community and vegetation ecosystems worldwide (Schneider, 1992; Klaučo et al., 2013, 2017; Wong et al., 2010; Lemenkova, 2022a; Hasanbegović et al., 2024). Concern about global warming and its effects on forest vegetation is widespread (Rodriguez-Franco & Haan, 2015; Stolte, 2001; Park et al., 2014). Many discussions have covered a wide range of topics regarding vegetation and land cover change under the effects of climate (Wang et al., 2025a; de la Huerta-Schliemann et al., 2025; Liu et al., 2025; Lemenkova 2024a, 2025a; Chia et al., 2014; Silapaswan et al., 2001). Nevertheless, little is known about the effects of the forest structure and lichen communities on climate warming. The underlying mechanisms that influence hydrological water cycle and tree composition in alpine forest ecosystems (tree age and height) is still unknown.

The ability to predict future consequences of climate change depends on thorough investigation of hydrological relationships and their modelling using advanced tools (Addae and Dragićević, 2022; Ni et al., 2024; Lemenkova, 2019a, 2019b; Addae et al., 2024). Biophysical relationships between forest and environment can enhance or diminish negative climate effects (Descals et al., 2023; Brašanac Bosanac et al., 2024; Thien and Phuong, 2023).

Coniferous forests are under pressure from global climate change and external forces (Lee et al., 2014; Diem, 2003). Specifically, mountainous forests mitigate warming through evaporation and cooling (Dimitrijević et al., 2023; Lemenkova 2022b; Huo et al., 2009). To evaluate current state of forests, the interdisciplinary research is required which uses advanced methods of modelling data (Lunnan et al., 2004). Boreal forests have significant biophysical effect on the biomes of Europe. This includes the impacts on annual mean temperature, precipitation and mitigation of climate extremes (Boisvenue et al., 2012; Cheng et al., 2015). Loss of boreal forest affects glaciation and increases warming. Through absorbing water by canopy and returning it to the atmosphere as vapor, mountain forests have a significant impact on water balance. This maintains water cycle and mitigates contrasts in temperature and precipitation. Besides, infiltration is also increased and runoff is decreased in mountain forests. The relevance of fog for water balance of temperate mountains of Alps is still unknown.

Forests in the 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. These high variations in cloudiness at small scales affect evaporation fluxes (Barr et al., 2021; Pattey et al., 1997). Estimation of these fluxes includes large uncertainties and is difficult to interpret (Wang et al., 2007; Beverland et al., 1996). To better evaluate such relationships, diverse modelling techniques to evaluate interacting climate factors and environmental variables should be considered (Barr et al., 1997; Lemenkova, 2019c, 2024b; Krstić 2024; Wang et al., 2025b; Ioniță et al., 2025). Modelling techniques investigate the impacts of global change to identify feedbacks from climate processes on ecosystems and the potential of forests to mitigate climate change (Pawendkisgou and Yaméogo, 2023; Lemenkova 2025b; Ozdemir and Abdikan, 2025).

The amount of water intercepted by the forest canopy varies with age, structure and leaf type (Hadiwijaya et al., 2021; Park and Hattori, 2004). Also, it depends on presence of mosses and epiphytes which may intercept water (Węgrzyn et al., 2012). Specifically, lichens and epiphytes store water inside the forest, sustain evapotranspiration, decrease Bowen ratio, and increase air humidity (Rouse & Kershaw, 1971). In this way, forests decrease water pressure deficit and create little water stress to leaves and epiphytes (Valladares et al., 2016; Jongman & Korsten, 2017). In temperate mountain forests needles sustain for years and epiphytes develop on boles and branches of old trees (Dettki et al., 2000; Giordani, 2012). In aged forests, lichens continue to grow on old plants and increase interception capacity, when stand leaf area index (LAI) has reached maximum. In this way, lichens and age of forests contribute to water balance and regulate climate parameters, which has also been reported earlier (Errington et al., 2022; Kentjens et al., 2023).

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2. Materials and methods

The experiment was conducted in South Tyrol, Italian Alps. The catchment has an area of 0.44 km^2. The water basin was measured on local DEM using ArcGIS. 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 decidua* Mill) trees. Scots pine (*Pinus sylvestris* L.) and European rowan (*Sorbus aucuparia* L.) were also presented occasionally. The dominant tree height was ca. 29 m. The understory consisted of alpenrose (*Rhododendron ferrugineum* L.) and 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 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 taxonom and on average consisted of 49% sand, 39% silt, and 12% clay.

We aimed to understand the potential influence of fog and tree age and the associated abundance of lichens on water balance. To estimate water balance, the relative contribution of the water components in the balance at the catchment level was measured. Fog had a noticeable impact under certain meteorological conditions. We assume that older trees have higher interception capacity and lower throughfall rates than younger stands. This is because of the epiphytic lichens in older forest. Positive feedback is established between the tree age and evaporation fluxes. To estimate fog water, it was derived from the comparison of the gross and net precipitation.

The traditional harvest method creates small gaps, ca. 50 m wide, and involves the thinning of trees (Connell et al., 2004; Jonsell & Rubene, 2024). The diameters and heights of trees were measured regularly following existing methods (Zhang et al., 2015; Stepper et al., 2016), while the diameter of a subset of trees is measured annually by manual dendrometers. The inventory (tree height, size and position) was performed using TruPulse sensor. In addition, tree size was assessed using a laser technique. The forest has heterogeneous vegetation structure, with even-aged groups at a larger scale. First group consists of old spruce trees with an age of ca. 200 years; second group consists of young, ca. 30 years-old trees were present at the study site. In both stands, parts of the living crown often reached the ground.

Water partitioning and water balance at catchment level

The water partitioning at catchment level was estimated considering existing similar works (Skalova et al., 2002; Shen et al., 2013) for old and young forest ('of' and 'yf') for five months. Total precipitation (P) was split into rain (Pr, mm) and mixed precipitation (Pm, mm) (only 9 days with fog-only), canopy interception (I, mm) was calculated as P - throughfall (Tf) - stemflow (Sf):

$$P = Pr + Pm + F = Tf + I + Sf \quad (1)$$

Total forest evapotranspiration (ET_EC) was considered to be the sum of tree transpiration (T), evaporation of intercepted water (I), transpiration of the understory (Tu), and soil evaporation (Es).

$$ET_{EC} = T + I + Tu + Es \quad (2)$$

ET_EC was measured for the whole forest using existing techniques of eddy covariance (Rummel et al., 2002; Kang et al., 2025; Yan et al., 2023), T for trees of the two stands using sap flow sensors, and I was equal to tree interception (as intercepted water will eventually evaporate) calculated from precipitation balance.

The sum of understory evaporation plus soil evaporation (Esu) was calculated as the residual of ET_EC - T - I.

$$Esu = ET_{EC} - T - I \quad (3)$$

Discharge (DC) and change of soil moisture (dSWC) were measured using existing techniques (Wu et al., 2019) for the whole forest.

The annual water balance was calculated following Eq.1,

$$Pr + Pm = ET_{EC} + dSWC + DC + DPe \quad (4)$$

where all acronyms are listed above except for DPe, which is deep percolation. All these terms were expressed in mm (1 mm = 1 kg m^{-2} of water).

To understand fog occurrence, meteorological conditions were compared during periods with dry conditions (dry), fog (<1 km visibility) and rainfall. These included relative humidity, TºC, radiation, wind speed and direction, ratio of diffuse to total global radiation and VPD. The influence of aged tree in water balance was evaluated by estimating and comparing water interception, epiphyte composition and TºC at different heights of canopy forest. The role and contribution of fog were estimated by its impact on throughfall. A linear regression equation was determined between throughfall and precipitation rate for mixed precipitation and rain-only events for both stands. These gave a predicted throughfall for a precipitation event with rain-only and with fog (mixed). 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. Additional measurements at soil level were performed in an old and young forest, in which soil moisture was measured. Water discharge was estimated at catchment level.

Evapotranspiration and tree transpiration

Evapotranspiration (ET_EC) was calculated from eddy covariance data following the ICOS setup and elaborated with Eddypro. Based on monthly energy balance ratio, we estimated the systematic errors in the eddy covariance measurements for LE+H as 17.6%. Given a Bowen ratio of ca. 1 in summer, this can be assumed to be half of this value in LE (8.8%). The random error of EC and the other components of the water balance was calculated statistically. Tree transpiration was estimated by measuring 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 showed a representative behaviour of these trees for their size classes. To minimize the errors caused by incoming shortwave radiation, one sensor of the tissue heat balance sensor was installed at 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}). 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 mean crown radius in the four cardinal directions. The average tree transpiration of the two smaller trees (DBH 23 cm and 32 cm) represented young stand, while the average of the larger trees (DBH 43 cm, 50 cm, and 57 cm) – old stand. All trees were dominant or codominant.

Local trees and spruces were characterized by an almost columnar shape. This shape and the high LAI (4.74 ± 0.88 for the 200-y.o. stand and 4.65 ± 0.86 for the 30-y.o. stand, as measured by hemispherical images), created microclimatic conditions in the crown, favouring lichen growth. 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-y.o. section and the 30-y.o. 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. Six tipping bucket pluviometers arranged 5 m apart in two groups of three recorded the below canopy precipitation at a 10-min resolution.

To increase collection representativeness, funnels with a diameter of 30 cm were placed above the orifice of each pluviometer. The periods characterized by dry conditions, with fog and with rain, were compared. These included both observation and prediction periods to assess the accuracy. The number of days characterized by dry conditions, fog, precipitation (rain or snowfall), and mixed precipitation were calculated.

Water storage capacity of lichens

The role of lichens in 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 lichens was assessed in spring on tree with 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 3-m sections. In each of them, all the branches were counted and all lichens present above a single 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. They were dried in an oven at 45 °C until a constant weight was achieved and then weighed to assess their dry weight.

3. Results and discussion

From January until August, the total fog frequency was 296.5 h during 72 days with fog and 37 days with mixed precipitation (109 days; 30% of days were foggy and 15% had mixed precipitation). Evaluated water components at canopy level are summarized in **Table 1**. The average monthly precipitation (monthly and max daily sum) and temperature (monthly and daily average) and for the long-term period are presented in **Fig. 1**.

The average monthly precipitation as a monthly sum and maximum daily sum, showed the importance of convective rainfall events in the warm summer, while cold winters were dry. The precipitation was in accordance with the 20-year average. Also, 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. Fog occurred for 241 h during 9 days with fog (5%) and 45 days with mixed precipitation (27%) within a period of 167 days (from late spring to autumn). The data are based on daily measurements divided into dry and precipitation periods. 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. Average values of radiation, relative humidity and vapour pressure deficit (VPD) during days with precipitation, fog and mixed precipitation were calculated to predict fog occurrence.

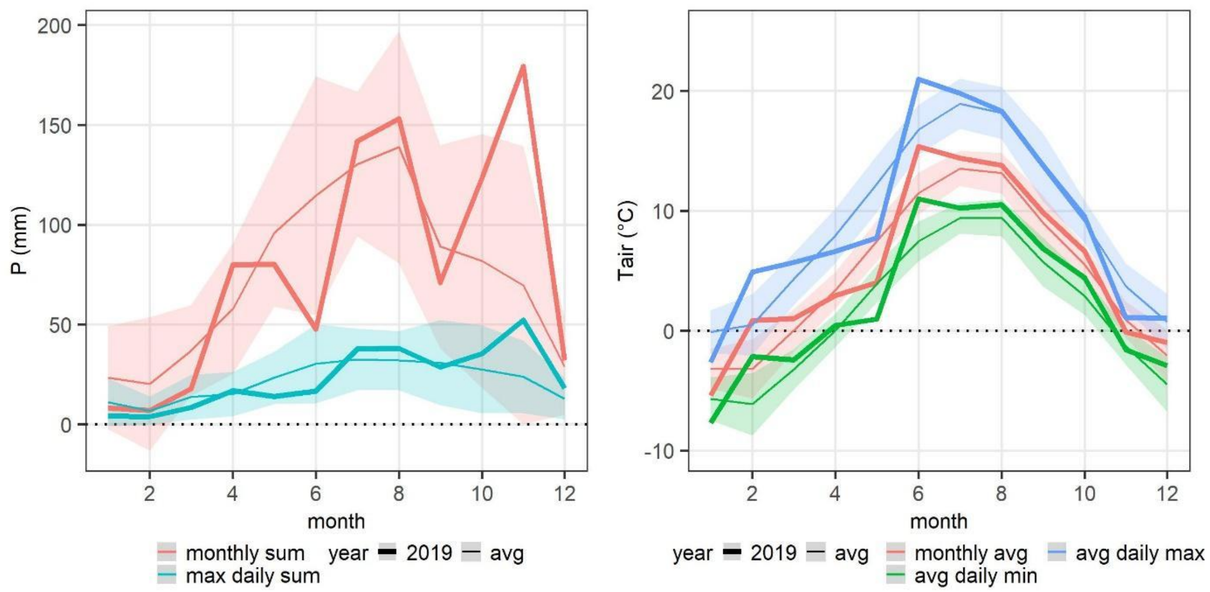

Fig. 1. Average monthly precipitation and temperature and for 2019 and long-term period

Table 1. Precipitation, evapotranspiration, throughfall, stemflow and interception

Period	Days	P	ET	Throughfall	Stemflow	Interception
			young forest			
dry	78	1.3 ± 1.8	350	2.6 ± 3.3	0.0	-1.3 ± 3.3
fog	8	0.1 ± 0.2	26	0.2 ± 0.0	0.0	-0.0 ± 0.2
mixed fog+P	42	460 ± 35	110	292 ± 26	1.0	167 ± 36
rain/snow only	34	132 ± 21	147	47 ± 11	0.1	85 ± 19
			old forest			
dry	78	1.3 ± 1.8	350	0.6 ± 0.2	0.0	0.7 ± 1.4
fog	8	0.1 ± 0.2	26	0.1 ± 0.0	0.0	0.1 ± 0.2
mixed fog+P	42	460 ± 35	110	216. ± 11	0.8	242 ± 29
rain/snow only	34	132 ± 21	147	36 ± 3	0.2	97 ± 16

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. These results highlight the importance of days having both fog and rainfall (mixed precipitation). Previous observations over 254 days were with cloudy conditions (70%) in South Tyrol but did not obtain fog or mixed precipitation. Days with fog (defined as days with fog and days with mixed precipitation) may account for 45% of cloudy days in 2011, **Table 1.**

Meteorological conditions during days with rain, fog, and mixed precipitation

Data variability is higher within the Rg dif/Rg tot ratio than within the RH and VPD. The 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. 2**. When accounting for the interception, tree transpiration contributed slightly less to ET than the soil and understory E(T), while there is a contribution of the understory that accounts for 10–70% of the total transpiration. Discharge (DC) and the change in soil moisture (dSWC) completed water balance, as both were measured for the entire forest, the same values were used for both stands. 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 and were levelled out over the entire measuring period. Average values of radiation, relative humidity and vapour pressure deficit (VPD) during days with precipitation, fog and mixed precipitation were calculated to predict fog occurrence in 2019. 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. Relative humidity exhibited the opposite pattern of T and VPD.

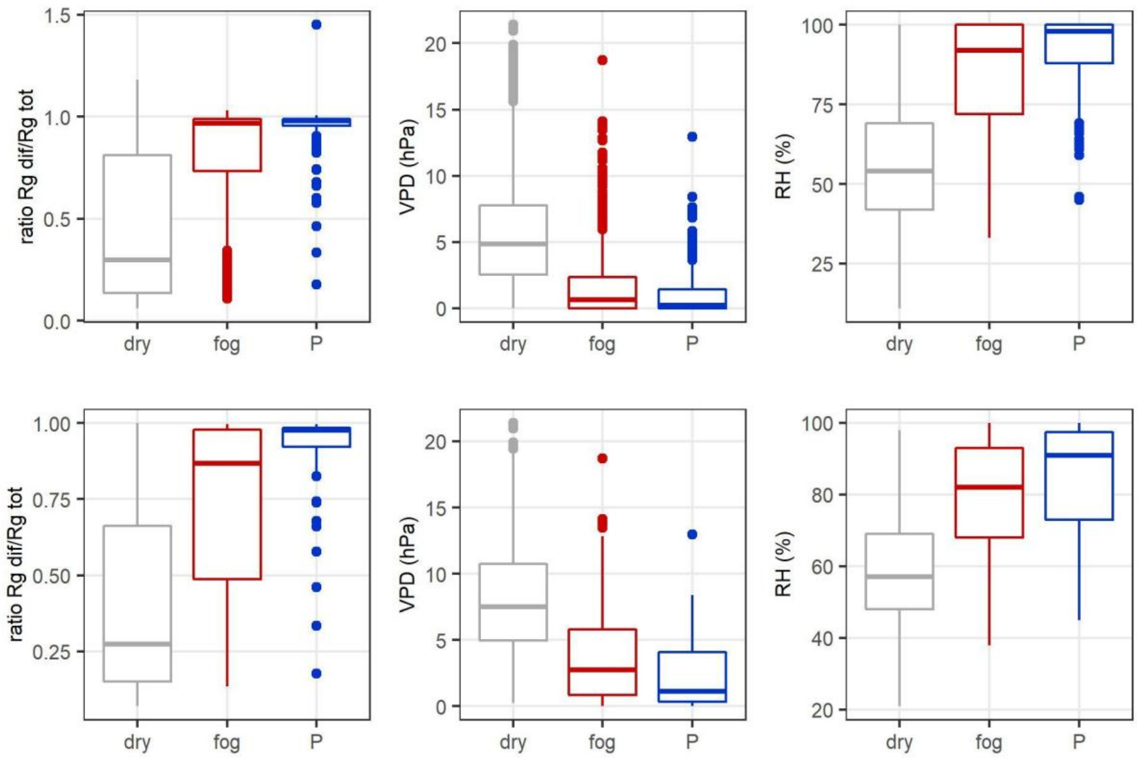

Fig. 2. Meteorological conditions (ratio of diffuse to total global radiation, vapor pressure deficit VPD, and relative air humidity RH) during periods with fog (less than 1 km visibility), precipitation, and dry conditions (dry) in winter (top row) and spring (bottom row)

The decrease in temperature was observed during the day but an increase during the night due to fog in long-term data, with different night sensitivity of temperature.

Uncertainties regarding the ability of sap flow measurements to predict absolute values led to an underestimation of tree transpiration.

Time course of radiation (total radiation top-left, diffuse 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 in late spring, end of May, the start of June (a.) and end of October, the start of November (b.) are presented in **figure 3**.

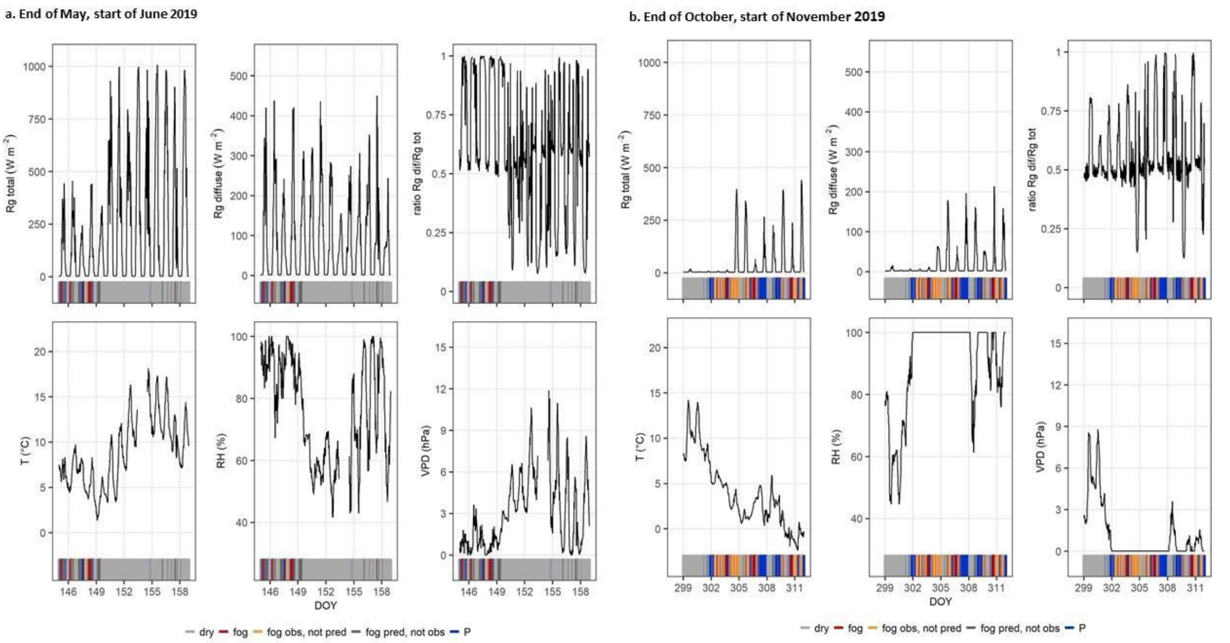

Fig. 3. Statistical analysis on data showing radiation, air temperature, humidity, and vapor pressure deficit (bottom right) during a foggy period, 2019

Canopy evapotranspiration and tree transpiration

Even though the precipitation totals were below the long-term average, rainfall events occurred quite regularly during the entire measuring period. The transpiration of the old (Tof) and young stand (Tyf) calculated from sap flow measurements was low compared to canopy evapotranspiration from eddy covariance. The time courses of T and ET corresponded to weather conditions and an overall decrease. 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 is lower because of lower temperature and phenology, **Fig. 4**. The 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. Neither ET nor T correlated with P. By splitting the days into dry, mixed precipitation (fog and precipitation), and with rainfall-only, it was found that, not

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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).

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 24% of additional throughfall compared to rain only events. Also important, fog was not considered in past studies. Thus, our 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. The measuring period (from 2019-5-30 until 2019-11-07) did not cover the entire year, the water balance for this period was not closed, with lower inputs (P = 593.6 ± 55.4 mm) than outputs (ET_EC + DS + dSWC = 689.6 ± 70.7 mm).

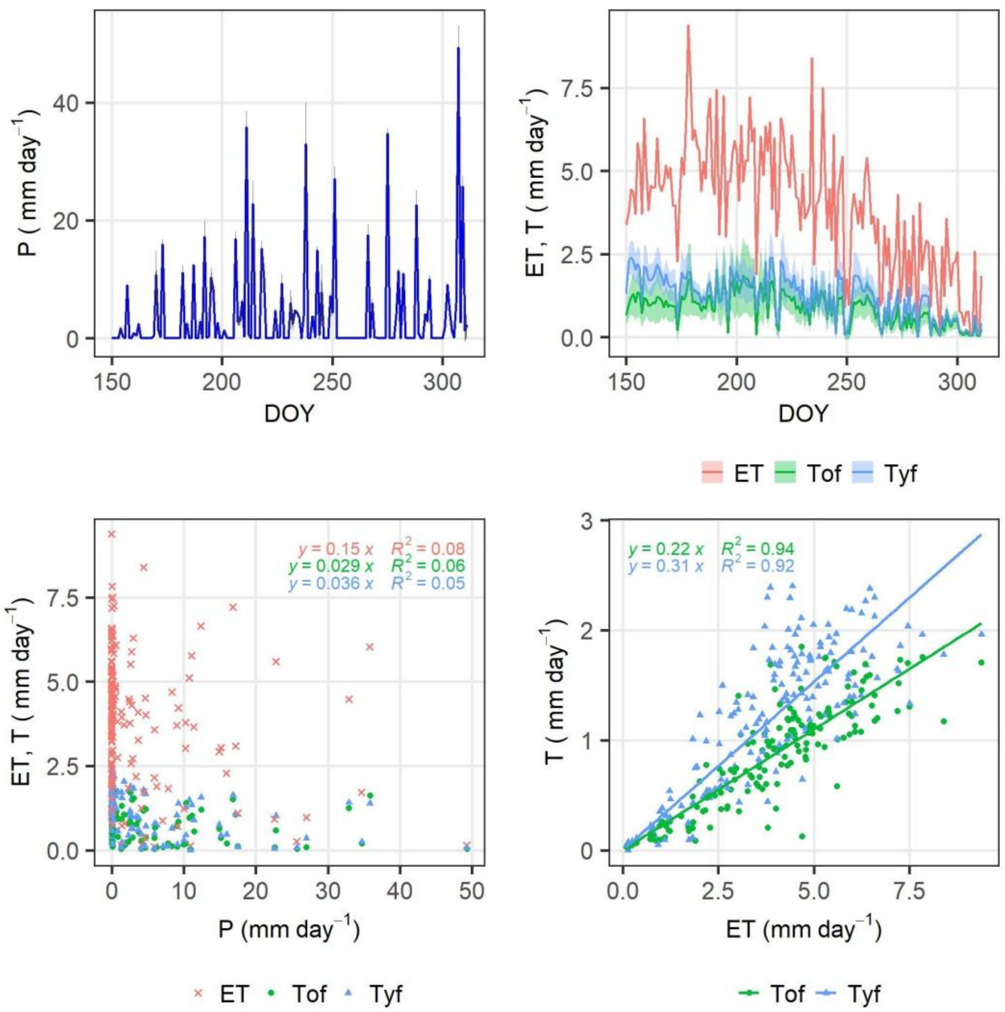

Fig. 4. Daily precipitation (P) and daily evapotranspiration measured with eddy covariance (ET) and daily transpiration for the old (Tof) and young (Tyf) forest upscaled from sap flow measurements (top right)

The frequency of fog events was quantified in a subalpine coniferous forest to assess the hydrological balance at basin and canopy scales. 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.

Water balance was almost closed for the entire 2019, with a difference of 25.4 mm between the input (P = 985.6 mm ± 82.3 mm) and output [ET_EC (804.9 mm ± 70.7 mm) + DS (167.0 mm ± 0.1 mm) + dSWC (40 mm ± 1 mm) = 1,011.9 mm ± 103.7 mm]. Deep percolation is reported to represent a large component of the hydrological balance at some sites, when water basin lays over a fractured bedrock. In this case, deep percolation is of minor importance.

The results demonstrated that 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. Additionally, mountain forests reduce runoff and increase infiltration. Warmer temperatures may have very distinct consequences for alpine forests, such as an increase in radial growth, which depends on water availability to compensate for the increased evapotranspiration.

The relevance of interception capacity was high when precipitation was low. Water was used to refill the canopy and soil reservoirs, without being lost as runoff. Large amount of water intercepted by the canopy represents most of the precipitation in the old stand, locally re-emitted as evaporation without stomatal control. It was shown that part of this water and fog can be directly taken by the plant for its needs. 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 to sustain positive feedback in the water cycle. It favors the presence of dense vegetation and lichens, and increases water vapour. As there is a reduction of water vapour in the air, the presence of old-growth vegetation represents a critical element for climate regulation in the Alpine region. This evidence proves the capacity of forests to regulate extreme heat conditions.

Conclusions

This paper demonstrated that forests serve as climate regulators through balancing water cycle through precipitation and evapotranspiration. Moisture availability needs to be considered to predict the consequences of climate change. Forest overuse and degradation can lead to environmental problems: soil erosion, landslides, rockfalls, increased water runoff or reduced water storage. Other problems may include the drying of springs, and biodiversity loss, and have severe impacts on livelihoods. Understanding water distribution in forests and its consequences is important for land-use management, water policies, and modelling climate system. Modelling enabled to quantify the capacity of the forest to intercept water in canopy. The estimate of this capacity was provided 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 identical in both 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 water cycle in the old section only and had a water-holding capacity of 0.6 mm for each precipitation event.

Combined with rainfall the same day, as mixed precipitation, fog contributes to higher throughfall, which increases net precipitation (soil water recharge) and evaporative conditions inside the canopy. Fog plays important role in water balance during days with mixed precipitation, maintaining high relative humidity inside the dense coniferous crowns of forest. This helped trees to maintain large leaf area, and the filamentous lichens to grow in the upper canopy. These two features led to a large capacity of the crown, particularly in the mature coniferous forest, to intercept liquid precipitation. Thus, it released only a small amount of precipitation to the soil and eventually to runoff, sustaining local ET with an associated reduction of the sensible heat flux.This research contributes to hydrological analyses and confirms that indicates that natural forests play a key role in dampening heat extremes above vegetated terrestrial ecosystems. It attributes to fog and cloudiness the role of linkage in positive feedback between forests and climate.

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