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Lichens and epiphytes as sentinel organisms for the determination of the water balance in forest ecosystems of South Tyrol

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ABSTRACT

Lichens and fog are one of the primary components of the water balance in the coniferous forest, which affect the hydrological cycle in the ecosystem. This paper investigates the role of fog during mixed rain-fog situations in an old-grown forest with presence of lichens – *Evernia divaricata* and *Pseudevernia furfuracea*. Fog represents a form of low-lying cloud and is greatly impacted by geographic setting, wind conditions, and water streams. Using methods of environmental statistics, the effect of forest stand age, fog, and abundance of lichens on the water balance were investigated. The results demonstrated that the presence of lichens and fog are related to humidity and maintains water balance in the forests of South Tyrol. Specifically, the interception was found to play a dominant role in the precipitation and evapotranspiration partitioning, especially in the older stand, where it was enhanced by lichens. Using modelling techniques, this study proved the importance of fog and lichens for the boreal forests ecosystems: fog transfers water from the atmosphere to the terrestrial surface, and lichens plays a significant role in increasing humidity in old stands.

Key words: lichens, remote sensing, image processing, satellite image, scripting language

Introduction

In a hydrological context, water balance refers to the volume of water inflows, outflows, and storage changes within a defined ecosystem over time (Skalova et al., 2022; Bréda et al., 2006). Changes in water balance components can affect forest ecosystem through water evaporation, precipitation or interception by plants. Lichens are capable of storing significant amounts of water. This capacity is related to the nature of lichens as poikilohydric organisms (Kumari et al., 2024). The internal water content in lichens fluctuates depending on the external hydrological and environmental settings, because these plant do not actively regulate their hydration (Nash et al., 1990). With this regards, epiphytes can intercept rainfall and change the amount and chemical composition of throughfall water. Such regulatory mechanism affect water balance and microclimate of forest ecosystems.

Lichens are essential to ecosystems because they help build soil, cycle nutrients, and are used in bio-monitoring projects to evaluate the sustainability of ecosystems, including air quality (Joly et al., 2010; Rodríguez-Quiel et al., 2019; Dunford et al., 2006). Lichens, while not directly performing transpiration, contribute significantly to evapotranspiration through their ability to absorb and release water and thus determine ecological processes (Asplund and Wardle, 2017). Evapotranspiration is an important process which includes evaporation as a physical phase and transpiration as a biological phase. Such mechanism refers to the phenomenon of water evaporating from the Earth's surface into the atmosphere and is crucial for the balance of forest ecosystems (Wang et al., 2014; Taheri et al., 2025; Benyon et al., 2015). As a mechanism for storing and releasing water, lichens affect local water cycle and may have an effect on the surrounding flora in the coniferous forests (Asplund & Wardle, 2013). Nevertheless, there is a lack of study on how lichens react physiologically to water exposure in their natural habitats. The majority of the previous studies were focused on water accumulation in lichens (Harris et al., 2018; Potkay et al., 2020) or trees that have artificial environments, such as transplanted lichens (Holopainen, 1984; Garty et al., 1998).

Lichens response to hydrological effects in the subalpine ecosystems is not studied sufficiently. At the same time, statistical methods are important to analyse data for revealing trends in environmental processes (Dale & Fortin, 2002; Duckworth, and Stephenson, 2002; Lemenkova, 2022a; Wang et al., 2010). Because of the growing interest in mathematical and cartographic methods in Earth sciences, long-tested methods (statistical, comparative, cartographic) are being actively used in environmental sciences (Lemenkova, 2022b, 2023a, 2023b). In order to close the existing knowledge gap and application of statistical methods to lichen research, we studied lichens from South Tyrol, mountainous region of Italy, and looked at whether physiological indicators like water content, growth of trees with different heights, and age could be used to identify differences in ambient. In this way, current research contributes to the environmental analysis of lichen, their capability to held water and distribution on trees with various age and height (Caruso and Thor, 2007).

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 (Ahmadjian, 1993; Yang et al., 2023; Lemenkova, 2025a; Tsai & Kuo, 2012). The physiological response of lichens to water content varies depending on where they are collected: water content is significantly impacted by tree height and precipitation (Kumar et al., 2022). Higher contents of water are linked to the extent of rainy days in lichens. Since natural lichens can detect even little changes in ambient water concentrations, our study demonstrates the usefulness of lichens as bioindicators (Gannutz, 1968; Djupström et al., 2010). This study shows the potential of lichens for further ecology research by showing which physiological variables might be employed as indicators of particular tree traits – height, age, leaves (Avalos et al., 1986).

Since lichens are sensitive to water and tree health, they are commonly acknowledged as bioindicators of environmental sustainability (Jairus et al., 2009; Carter et al., 2017). As a result, their distribution and health can be utilized to track the forest stands' air quality. Prolonged humidity is a major environmental stressor that damages trees and ecosystems. It builds up in lichens and alters their physiology in a number of ways. Fine particles containing water can be deposited on the surface of lichens and in the intercellular spaces of their medulla, where they can stay unchanged for extended periods of time.

In this work, we aimed to answer the following questions: (1) What is the contribution of fog and lichens to the water balance of the coniferous forests? (2) How does the presence of epiphytes affect the water supply to the boreal coniferous ecosystems?

Materials and Methods

This paper aimed to better understand the potential influence of fog and tree age and the associated abundance of lichens on the water balance. To estimate the water balance, we measured the relative contribution of the water components in the balance at the catchment level. Water storage capacity of lichens was investigated using Eddy covariance technique. This technique is used to quantify the energy and gas exchange between the atmosphere and the Earth's surface (Burba, 2022). In this study, the turbulent air flows (eddies) were measured as and scalar entities using sonic anemometers and gas analyser to calculate fluxes. Using Eddy covariance, the values of fluxes of the environmental properties are obtained as high-frequency wind and scalar atmospheric data series, including data on gas and energy fluxes, as described in previous studies (Bond-Lamberty, 2018; Dias et al., 2007; Guenther and Hills, 1998). Local trees and spruces were characterised by an almost columnar shape (Marcolla et al., 2005). This shape and the high leaf area index (LAI) (4.74 ± 0.88 for the 200-year-old stand and 4.65 ± 0.86 for the 30-year-old stand, as measured by hemispherical images), created peculiar microclimatic conditions within the crown, possibly favouring lichen growth, Figure 1.

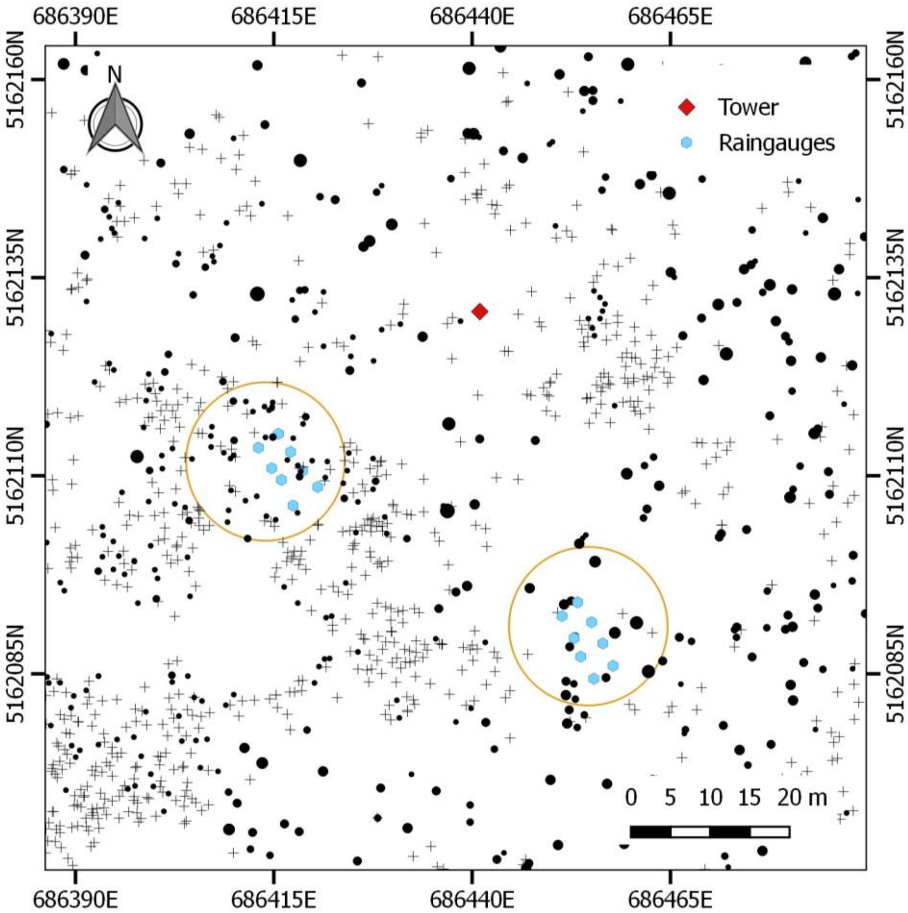

Figure 1. Map with topographic location of trees with lichens in the measurement set

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. To characterize 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 (Table 3). The temperature was not significantly different outside and inside the canopy, which correlates with previous research (Campbell and Coxson, 2001). 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.

Results and Discussion

The results shown that forest stands with older trees (≥200 years) have higher interception capacity and lower throughfall rates than younger stands in part due to the presence of epiphytic lichens in older forest. Besides, fog plays an important role in the water balance during numerous days with mixed precipitation, maintaining for several days a high relative humidity inside the dense coniferous crowns composing the forest, Table 1. This helped the trees to maintain a large amount of leaf area, and the filamentous lichens to grow in the upper part of the canopy (branches, all trunk, or their cumulative variable), Figure 2. These two features led to a large capacity of the crown, particularly in the mature coniferous forest, to intercept liquid precipitation, release 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.

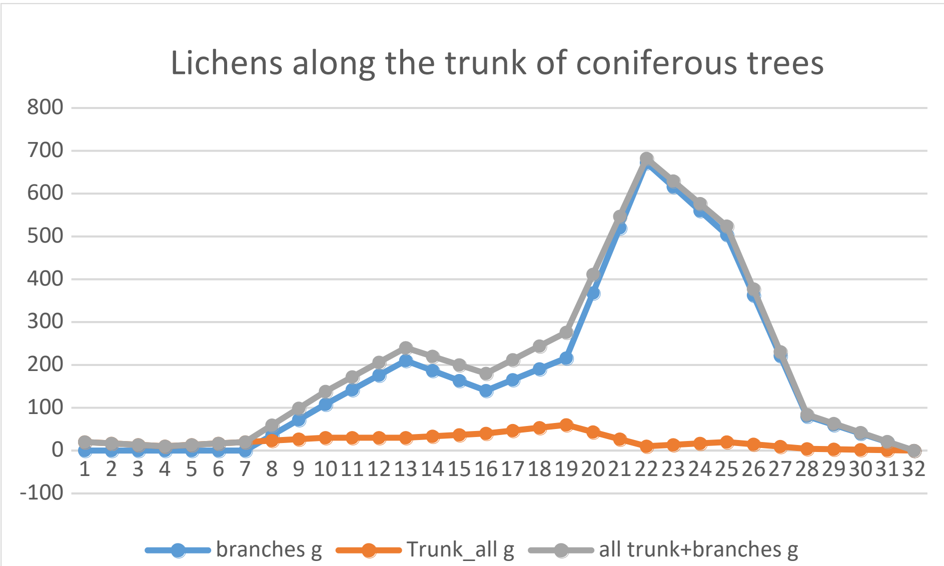

Figure 2. Distribution of lichens along the tree trunk of the coniferous forests

The philological characteristics were obtained and summarised in Table 1. Due to their protected status, we did not conduct a systematic survey on lichens, but we collected them from one fallen tree representative of the old forest. This tree held 7.26 kg of dry lichens; 0.71 kg (10%) of them were located on the trunk and the rest on the branches with the highest concentration located at 22 m above the soil at approximately ¾ of the tree height (Lemenkova, 2025c). Once rewetted, the lichens reached a fresh weight of 19.63 kg, thereby holding 12.37 kg of water; however, they lost ⅔ of that water again within two days when air-dried.

Table 1: Characteristics of lichens and their capacity of water retain

Total lichens dry weight in g on a 52 cm diameter tree	6544
Total lichens fresh weight in g on a 52 cm diameter tree	19632
Total water held by lichens in a 52 cm diameter tree (kg)	7,276E-15
Water mm (or kg m^{-2}) held by lichens	2,91E-12
Water availability as annual liquid precipitation events	200
Total intercepted water by lichens (mm y^{-1})	5,821E-14

The abundance of lichens in the old but not in the young stand could be a major reason for lower throughfall rates indicating a higher interception capacity in the old stand, even though leaf area index (LAI) was similar in both stands. Indeed, rainfall partitioning processes by trees differs as throughfall processes in response to rainfall depth, leaf type and phenological periods, bark texture, and LAI (Beidokhti and Moore, 2021). 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 (Lemenkova, 2025b).

Table 2: Lichens in the net

Lichens in the net	**ID Nr.**	**With net, saturated of water (g)**
29.06.20	h12	286
29.06.20	h22	142
30.06.20	h12	126
30.06.20	h22	96

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, Table 2. 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 different heights of trees (m), Table 3. To this end, a combination of temperature sensors and hygrometers was integrated into a single device for data capture using instruments designed for environmental monitoring.

Table 3: Characteristics of the measured occurrence of lichens on trees with different heights. Lichens weight is given on the sampled branch; number of branches is estimated for 1 m vertical section; weight (g) of lichens is calculated on 1 m vertical section

Height of trees (m)	ID Nr.	0.1 m section half-circumference	Lichens weight on 1 m section g	Trunk_all g	Lichens weight g	No of branches	Weight (g) of lichens	Branches_ all
0.9-1	0	1	20	20	0		0	0
	1			16,66			0	0
	2			13,33			0	0
3.9-4	3	0,5	10	10	0		0	0
	4			13,3			0	0
	5			16,66			0	0
6.9-7	6	1	20	20	0		0	0
	7			23,33				36
	8			26,66				72
9.9-10	9	1,5	30	30	12	9	270	108
	10			30				142
	11			30				176
12.9-13	12	1,5	30	30	14	15	450	210
	13			33,33				186,66
	14			36,66				163,33
15.9-16	15	2	40	40	20	7	280	140
	16			46,66				165,333
	17			53,33				190,66
18.9-19	18	3	60	60	36	6	360	216
	19			43,33				368
	20			26,66				520
21.9-22	21	0,5	10	9,99	56	12	120	672
	22			13,33				616
	23			16,66				560
24.9-25	24	1	20	20	42	12	240	504
	25			14,66				362,66
	26			9,33				221,33
27.9-28 m	27	0,2	4	4	10	8	32	80
	28			3				60
	29			2				40
	30			1	0	0		20
	31	0	0	1,24	0	0	0	-1,7

The results revealed (Tables 1, 2 and 3) that lichens play an important and underestimated role in the regulation of water balance in older parts of our forest. 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. This can be explained by the mechanism of water capture by interception in the tree canopies. Hence, it plays a certain role in evapotranspiration, however the impact is generally less significant than transpiration from trees and evaporation from the soil and understory. In contrast, Transpiration refers to the fact that trees transpire water from their leaves, returning water to the atmosphere during periods of moist soil. 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. For example, micro-meteorological conditions, such as vapour pressure deficit, are key determinants of transpirational cooling in forest stands. Besides, the tree age has significant effect on the hydrology, because younger trees have less drought stress due to reduced surface sealing (Tams et al., 2024). Possibilities for in situ calibration and realistic estimation of measurement errors are still open for examination in sap flow research.

Our findings demonstrate the value of lichens as one of the important regulators and determinators of water source in the region of Dolomites, northern Italy, where lichens increased in the old stand forest which correlated to higher humidity. Prior research has generally recognised the significance of lichens (e.g., Pérez et al., 2024; Hämäläinen and Fahrig, 2024; Soleimannejad et al., 2025). Lichens are acknowledged as vital components of forest ecosystems. In view of the existing limitations of relevant studies on lichens and difficulty in their fieldwork measurement and evaluation, this paper contributed to our understanding of the role of lichens in the European forests with an example of Italy.

The biosphere of the coniferous forests is a natural model system that reflects the environmental change. Understanding the water balance, hydrology and plant health in forests can support monitoring of the biodiversity changes. Moreover, it is useful for ecosystem function services and maintaining multi-variable analysis in silviculture research. Therefore, understanding the role of ecosystem components, such as lichens or fog, to the ecosystem balance enables to correctly estimate aboveground and belowground processes. Data integration and modelling indicate that forest ecosystem is an complex nonlinear system with exceptional functionality. This paper contributes to the sustainable forest monitoring. Finally, we demonstrated the effects of individual components of forest ecosystems, such as functional groups and lichen species, on the balance of the whole structure.

Conclusion

In this study, the capacity of the forest was quantified to intercept water in the canopy, and an estimate of this capacity was provided in the two different forest stands, old (200-year) and young (30-year) stand, which continues existing studies on lichen-tree relationships (Cleavitt et al., 2009). The higher water storage capacity of the old stand did not depend on the LAI, which was identical in the two stands, but on the other structures, mainly epiphytes. Such organisms, typically represented by filamentous lichens, e.g., *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. Lichens are a unique symbiosis of specialised fungi with photoautotrophic components, which may include other lichens and affect hydrology of tree tranks (Furmanek et al., 2019; Aslan et al., 2006).
The relevance of this interception capacity was particularly high when precipitation was light (based on field observations) and compared to other research (Jayalal et al., 2012). Interception refers to

water that is temporarily held on the surfaces of vegetation (like leaves) and then evaporates back into the atmosphere, rather than reaching the ground. In our 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 (Caruso et al., 2008). In addition, in some ecosystem types, part of this water and fog can be directly taken by the plant for its needs (Bruijnzeel et al., 2005). This study proved that the role of lichens is to sustain positive feedback in water cycle, favouring the presence of dense vegetation, and increasing water vapour, which is in line with the previous studies (Dietz and Hartung, 1998; Porada et al., 2014;).

In order to effectively identify environmental characteristics and their relationship with meteorological conditions, it is essential to understand diversity patterns and the co-variation of different ecological parameters (Klaučo et al., 2013; Su et al., 2019; Wang et al., 2025; Lemenkova, 2023c, 2023d). In this study, we analysed the extent to which lichens co-vary with characteristics of trees, their ability to correlate with other parameters in a studied network, and their patterns of diversity with regards to tree age and stand structure. Since there is now 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 (Clement & Shaw, 1999; Gupta et al., 2007). This evidence is in line with recent studies indicating the capacity of natural forests to regulate extreme heat conditions. In view of this, this paper contributes to the better understanding of the role of trees and tree heights to the distribution of lichens that plays regulatory role in water balance in the forests of subalpine ecosystems of South Tyrol, Italy.

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Lišajevi i epifiti kao organizmi čuvari za određivanje vodnog bilansa u šumskim ekosistemima Južnog Tirola

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IZVOD

Lišajevi i magla su jedna od primarnih komponenti vodnog bilansa u četinarskoj šumi, koje utiču na hidrološki ciklus u ekosistemu. Ovaj rad istražuje ulogu magle tokom mješovitih situacija kiše i magle u staroj šumi s prisustvom lišajeva - *Evernia divaricata* i *Pseudevernia furfuracea*. Magla predstavlja oblik niskoležećih oblaka i na nju uveliko utiču geografski položaj, uslovi vjetra i vodotoci. Korištenjem metoda statistike okoliša istražen je uticaj starosti šumske sastojine, magle i brojnosti lišajeva na vodni bilans. Rezultati su pokazali da je prisustvo lišajeva i magle povezano s vlagom i održava vodni bilans u šumama Južnog Tirola. Konkretno, utvrđeno je da intercepcija igra dominantnu ulogu u podjeli padavina i evapotranspiracije, posebno u starijoj sastojini, gdje je pojačana lišajevima. Korištenjem tehnika modeliranja, ova studija je dokazala važnost magle i lišajeva za ekosisteme borealnih šuma: magla prenosi vodu iz atmosfere na površinu Zemlje, a lišajevi igraju značajnu ulogu u povećanju vlažnosti u starim sastojinama.

Ključne riječi: lišajevi, daljinsko istraživanje, obrada slike, satelitska slika, skriptni jezik

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