Response to referee comments and suggestions on bg-2018-521 by N. Löbs et al.: "Microclimatic conditions and water content fluctuations experienced by epiphytic bryophytes in an Amazonian rain forest"

Dear Professor Bahn,

we would like to thank you and the reviewers for the manuscript evaluation and the comments, which helped once again to improve our manuscript. We appreciate the opportunity to revise our manuscript one last time to address the constructive comments and suggestions from the reviewers. We once again worked intensively with the data, and believe that we now could solve all the remaining issues. Below we respond with a point-by-point explanation to the comments from the peer-reviewer with our responses in blue color following every comment. At the end of the comments we provide the manuscript and the supplement with all changes being marked.

Sincerely,

Nina Löbs, on behalf of the co-authors.

Comments on the text:
Black text shows the original referee comment, and blue text shows the response of the authors and the explicit changes in the revised text. The figure and table numbers refer to the revised manuscript with the marked changes.

Referee report #2

Maaike Bader, 06 April 2020

Dear authors,

In the new revised version a lot of the issues in the previous one have been addressed. I still think that the water-content data for the bryophytes are a unique and interesting data set. My main concern remains however, but I hope it can still be solved:

The impossibly high water contents of the air-dry liverworts in the canopy are still presented, and although the strangeness of the values is discussed (not convincingly), the values are not discarded or further corrected. I really think that data about the course of the water content of tropical bryophytes is very valuable and needs to be published, but these values must clearly be wrong, so they should NOT be presented as they are. Figure S5 gives a hint about what the cause of the strange values may be: Due to the unexplained short-term fluctuations, the water content, and thus apparently the electrical conductivity (EC) values, for the samples at 23m vary a lot around the half-hour mean. If we assume that the half-hour mean is the most realistic real EC value and that the short-term variations are noise, it is not a good idea to take the 5-minutes-based minimum and maximum (even not using a 1 or 5%, 95% or 99%

or whatever percentile) values for the calibration, because that way the noise is going to determine the calculated water contents. I hope I made the problem clear.

Dear Maaike Bader, following your suggestion, we carefully checked the data of all sensors again and decided not to use the data of some sensors and to exclude the data of the 18 m level from the analysis, as the larger fluctuations there could not be completely explained by us. We now included a new Figure S5, which shows the information used for data evaluation and calibration, i.e., the rainfall data, the raw EC values, and the calculated WC data. With this information, one could confirm the sensor's response to rain, and the overall response of each sample. In order to minimize the noise, only the 30-min averages were used for all new calculations and figures, as stated in the text.

For sensor #23 at the 23 m level we present a close-up view, which illustrates that the remaining "scatter" is caused by a pattern of daily fluctuations of the water content.

Another possible problem is that the very high WCmax of Symbiezidium that you determined in your calibration measurements (which does NOT mean that they would have a WC of 400% when air dry!) does cause a high calculated WC if a linear relationship between EC and WC is assumed, which is not realistic for the very high WCs. So here, you might need to start the linear part of the calibration curve at a lower WC.

We agree with your comment, and we altered the calibration accordingly. We now assume that all samples get completely dry at least once during the measurement period and this minimum electrical conductivity now corresponds to a water content of 0%. The material and methods section has been adapted accordingly and the new values are presented in Table S1.

I do not know if it will be possible to get a value for the water content that is reliable in absolute terms. Perhaps your best bet is to not even try and to only report on the fluctuations, i.e. wetting after rain (which I consider a clear and undisputed signal) and daily fluctuations at 23 m (which in my mind may reflect the equilibration with fluctuating air humidity, already indicating that it cannot be true that the WC is around 400, because at that value they would be wetter than in equilibrium with moist air. Information about such fluctuations is already interesting as a first bit of data, as it shows e.g. how long mosses stay wet after a rain. Because of the lack of replication and different positions of the bryophytes on the trunk it is indeed hard to attribute these patterns to the height on the tree, but even without that, it gives an indication of the patterns that are possible in rain forest epiphytes. In summary: either correct the values based on a new calibration (which should of course still be consistent and rational and not just a fine-tuning to get the desired result), or present the WC fluctuations without quantifying the absolute values.

As described above, the calibration was recalculated using only the 30-min averaged data and an adapted calibration method. In the figures 1, 2 and S6 the general WC patterns are shown for the different heights and seasons.

You can really emphasize harder that the type of data you present is unique. Microclimate has been measured in vertical profiles in rain forests before, but data on the temperature and water content fluctuations inside mosses, which are very relevant for estimating or modelling their productivity, have never been measured for so long or along a height profile, as far as I know. In the last paragraph of the introduction, make clearer why these data are exciting.

The last paragraph of the introduction was modified accordingly, as follows: (P3, L30-P4 L4 in document with marked changes) “In the current study, long-term continuous measurements of temperature, light and water content inside bryophyte communities have been conducted along a vertical gradient. To our knowledge, our study is the first one measuring microclimatic parameters and the water status inside bryophyte communities in a rainforest environment. With these data on the microclimate along a vertical profile and during different seasons, we believe to provide a unique dataset, combined with an estimation of the activity patterns of bryophyte communities in a tropical rainforest. ”

In the discussion (par 4.1) make clearer what the previous studies did and did not measure.

The text was modified according to the suggestion, as follows: (P14, L17-24) “In the current study we measured the microclimatic conditions experienced by epiphytic bryophyte communities along a vertical gradient over the course of more than two years. In previous studies, microclimatic data on the light, temperature, and air humidity have been assessed at different height levels within the forest (Chazdon and Fetcher, 1984; Lösch et al., 1994; Romero et al., 2006), but long-term measurements of the water content and the light and temperature on top and inside the cryptogamic communities and have been missing up to now.”

Another major point is that the presentation of the estimated potential physiological activity (Par 3.2 and 4.2) needs some reformulation in the sense that the compensation points should be consequently presented as rough proposals, not as values that you know to be valid for your environment or species. So try to use formulations like “If we assume a WCP of X (REF), the duration of activity would be Y”. Adjust in the caption of Fig 4 too. Also, 4.2. is quite long considering how little data you have to really be able to discuss this.

The sections 3.2 and 4.2 were reformulated, following the suggestion. The caption of the Fig 4 was also changed accordingly.

Some smaller remarks:

P2 L24-27 These introductory sentences are not really necessary.

Thanks for the suggestion, the introductory sentences were removed from the text (P2, L24-27).

P3 L15 a paragraph break is needed here. L15-17 are not necessary.

The alterations were made accordingly.

P5 L23 Expressing the oscillations in terms of WC would assume that the WC is correctly determined. Better express it as EC, and take it into consideration when calculating WC (see above)

The alteration was done accordingly (P5, L33).

P6 L10 what is this conversion factor base on?

Measurements of electrical conductivity also show a temperature-dependency, which needs to be considered during data analysis. For this, an exponential model type has been established by Sheets & Hendrickx (1995), as presented in Corwin & Lesch (2005). Ma et al. (2011) evaluated different models for electrical conductivity measurements and determined one as being best suited for the temperature correction of electrical conductivity measurements. This correction factor also proved to work fine on our data. This is explained in detail in Weber et al. (2016).

P6 L15-25 This section does not yet describe the calibration. This is described on P7 L1-14

This is correct. We now write "To determine the maximum water content of the different bryophyte communities, samples of them were collected in the forest area sur-rounding the ATTO site." (P6, L26-27).

P7 L15 Explain the origin of the oscillations and take them into account for determining the WC

This was done accordingly (P7, L28-32): "The measured electrical conductivity values showed short-time oscillations, which might be caused by the fact that the bryophytes cushions have some air spaces in-between, as we observed that these oscillations are less pronounced in denser substrate. Nevertheless, the overall functionality of the sensors is still ensured also in less dense material, and the short-term fluctuations could be removed with a 30-minute smoothing algorithm (Fig. S5). Thus, for all calculations the 30-minute averages were used.

P7 L18-19 Huge error bars suggest that this averaging may not be justified. Can you argue that it is? How are different species at one height a uniform group?

The dataset was double checked, and sensors with large fluctuations that could not be justified by the meteorological parameters were excluded from the calculations. The Figure S5 presents the remaining sensors with their raw EC values. After these recalculations the error bars are much smaller now.

P13 L13-16 You could use these results to your advantage by pointing out how they show the larger small-scale variation in environmental conditions du to shading and tree topography, which may cause conditions to be more variable within centimetres than the ´microclimate´ along the larger height gradient along the tree.

The suggestion was added to the discussion section: (P14, L30 – P15, L2) "Within one height level, the small-scale environmental conditions, such as radiation and shading, water conditions, and wind velocity vary, depending on the specific habitat conditions, as e.g. exposition, tree foliage and inclination of the substrate (Barkman, 1958; Campos et al., 2019; Cornelissen and ter Steege, 1989; de Oliveira and de

Oliveira, 2016; Sierra et al., 2018). These small-scale patterns also explain the variability within one height level. ”

P15 L12 After reinstallation, without recalibration, these values are no longer usable, I would just not present them.

This was done accordingly and the data are not presented anymore.

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Microclimatic conditions and water content fluctuations experienced by epiphytic bryophytes in an Amazonian rain forest

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Abstract. In the Amazonian rain forest, major parts of trees and shrubs are covered by epiphytic cryptogams of great taxonomic variety, but their relevance in biosphere-atmosphere exchange, climate processes, and nutrient cycling are largely unknown. As cryptogams are poikilohydric organisms, they are physiologically active only under moist conditions. Thus, information on their water content, as well as temperature and light conditions experienced by them are essential to analyze their impact on local, regional, and even global biogeochemical processes. In this study, we present ~~unique~~ data~~set~~ on the microclimatic conditions, including water content, temperature, and light conditions experienced by epiphytic bryophytes along a vertical gradient and combine these with above-canopy climate data collected at the *Amazon Tall Tower Observatory* (*ATTO*) in the Amazonian rain forest between October 2014 and December 2016. While the monthly average of above-canopy light intensities revealed only minor fluctuations over the course of the year, the light intensities experienced by the bryophytes varied depending on the location within the canopy, probably caused by individual shading by vegetation. In the understory (1.5 m), monthly average light intensities were similar throughout the year and individual values were extremely low, remaining below 3 µmol m^{-2} s^{-1} photosynthetic photon flux density during more than 84 % of the time. Temperatures showed only minor variations throughout the year with higher values and larger height-dependent differences during the dry season. The indirectly assessed water contents of bryophytes varied depending on precipitation, air humidity, and bryophyte type. Whereas bryophytes ~~at~~ in the canopy were affected by diel fluctuations of the relative humidity, those close to the forest floor mainly responded to rainfall patterns. In general, bryophytes growing close to the forest floor were limited by light availability, while those growing in the canopy had to withstand larger variations in microclimatic conditions, especially during the dry season. For further research in this field, these data may be combined with CO_2 gas exchange measurements~~,~~ to investigate the role of bryophytes in various biosphere-atmosphere exchange processes, and could be a tool to understand the functioning of the epiphytic community in greater detail.

1 Introduction

~~Cryptogamic communities comprise photosynthesizing organisms, i.e. cyanobacteria, algae, lichens, and bryophytes, which grow together with heterotrophic fungi, other bacteria, and archaea. They can colonize different substrates, such as soil, rock, and plant surfaces in almost all habitats throughout the world (Büdel, 2002; Elbert et al., 2012; Freiberg, 1999).~~ Epiphytic bryophyte communities ~~In the tropics,~~ ~~epiphytic bryophyte communities~~ widely cover the stems and branches of trees in the tropics (Campos et al., 2015). Within that habitat, they may play a prominent role in environmental nutrient cycling (Coxson et al., 1992) and also influence the microclimate within the forest (Porada et al., 2019), thus contributing to the overall fitness of the host plants and the surrounding vegetation (Zartman, 2003). However, they are also affected by deforestation and increasing forest fragmentation (Zartman, 2003; Zotz et al., 1997).

Physiologically, cryptogamic organisms are characterized by their poikilohydric nature, as they do not actively regulate their water status but passively follow the water conditions of their surrounding environment (Walter and Stadelmann, 1968). In a dry state, many of them can outlast extreme weather conditions, being reactivated by water (Oliver et al., 2005; Proctor, 2000; Proctor et al., 2007; Seel et al., 1992), and for several species even fog and dew can serve as a source of water (Lancaster et al., 1984; Lange et al., 2006; Lange and Kilian, 1985; Reiter et al., 2008). In contrast, high water contents (WC) may cause suprasaturation, when gas diffusion is restrained, causing reduced CO_2 gas exchange rates (Cowan et al., 1992; Lange and Tenhunen, 1981; Snelgar et al., 1981) and even ethanolic fermentation, as shown for lichens (Wilske et al., 2001). Accordingly, their physiological activity is primarily regulated by the presence of water and only secondarily by light and temperature (Lange et al., 1996, 1998, 2000; Rodriguez-Iturbe et al., 1999).

In the Amazonian rain forest, cryptogamic communities mainly occur epiphytically on the stems, branches, and even leaves of trees, and in open forest fractions they may also occur on the soil (Richards, 1954). By 2013, 800 species of mosses and liverworts, 250 lichen species, and 1,800 fungal species have been reported for the Amazon region (Campos et al., 2015; Gradstein et al., 2001; Komposch and Hafellner, 2000; Normann et al., 2010; Piepenbring, 2007). Whereas s~~S~~tudies in temperate zones address the importance of cryptogamic communities for the ecosystem (Gimeno et al., 2017; Rastogi et al., 2018), ~~but for the tropical area,~~ only few reports for the tropical region can be found in the literature.

~~Tropical rain forests are characterized by humid conditions, high temperatures with minor annual fluctuations, and an immense species diversity of flora and fauna. Currently, between 16,000 and 25,000 tree species have been estimated for the Amazonian rain forest (Hubbell et al., 2008; ter Steege et al., 2013).~~ The Amazonian rain forest has been described to play important roles in the water cycle, as well as in carbon, nitrogen, and phosphorus fluxes on regional and global scales (Andreae et al., 2015). Up to now, the relevance of cryptogamic communities in these regional cycling processes are largely unknown (Hargis et al., 2019). ~~However~~This data are urgently needed, as this ecosystem is under severe pressure and it is ~~also~~ hard to predict to which extent the ongoing and envisioned environmental changes will still ensure its ecological services as the "green lung" and carbon sink of planet Earth (Soepadmo, 1993).

~~Studies in temperate zones address the importance of cryptogamic communities for the ecosystem (Gimeno et al., 2017; Rastogi et al., 2018), but for the tropical area, only few reports can be found in the literature.~~ ~~There is a lack of information regarding the microclimatic conditions of the habitats colonized by cryptogamic communities in the tropics.~~ In the current study~~Thus~~, ~~with the~~ long-term continuous measurements of temperature, light and water content inside bryophyte communities have been conducted along a vertical gradient.~~,~~ To our knowledge, our study is the first one measuring microclimatic parameters and the water status inside bryophyte communities in a rain-forest environment~~are presented here~~ ~~for the first time~~. ~~, we aim to provide~~With these data on ~~seasonality patterns and the vertical profile of~~ the microclimate along a vertical profile and during different seasons~~within the canopy~~, we ~~aim~~believe to provide a unique dataset, combined with ~~. In the current study, we present the microclimatic conditions, comprising the temperature, light, and WC of epiphytic bryophyte communities along a vertical gradient and~~ an estimation of the~~ir~~ activity patterns of bryophyte communities~~in response to seasonal variations in climatic conditions~~ in a tropical rainforest.

2 Material and Methods

2.1 Study site

The study site is located within a *terra firme* (plateau) forest area in the Amazonian rain forest, approx. 150 km northeast of Manaus, Brazil. The average annual rainfall is 2,540 mm a^{-1} (de Ribeiro, 1984), reaching its monthly maximum of ~ 335 mm in the wet (February to May) and its minimum of ~ 47 mm in the dry season (August to November) (Andreae et al., 2015). These main seasons are linked by transitional periods covering June and July after the wet and December and January after the dry season (Andreae et al., 2015; Martin et al., 2010; Pöhlker et al., 2016). The *terra firme* forest has an average growth height of ~ 21 meters, a tree density of ~ 598 trees ha^{-1}, and harbors around 4,590 tree species on an area of ~ 3,784,000 km^2, thus comprising a very high species richness compared to other forest types (McWilliam et al., 1993; ter Steege et al., 2013). Measurements were conducted at the research site *ATTO* (*Amazon Tall Tower Observatory*; S 02° 08.602', W 59° 00.033', 130 m a. s. l.), which has been fully described by Andreae and co-authors (2015). It comprises one walk-up tower and one mast of 80 m each, being operational since 2012, and a 325 m tower, which has been erected in 2015. The ATTO research platform has been established to investigate the functioning of tropical forests within the Earth system. It is operated to conduct basic research on greenhouse gas as well as reactive gas exchange between forests and the atmosphere and contributes to our understanding of climate interactions driven by carbon exchange, atmospheric chemistry, aerosol production, and cloud condensation.

2.2 Microclimatic conditions within epiphytic habitat

The parameters temperature and light within/on top of the bryophyte communities and their WC were measured with a microclimate station installed in September 2014 (Fig. S1). The sensors were placed along a vertical gradient at ~ 1.5, 8, ~~18,~~ and 23 m above the ground on one tree, corresponding to the zones 1, 2 and ~~to~~ 4 (i.e., at the base, the lower trunk, ~~the upper trunk,~~ and at the base of the crown) ~~used~~ described by Mota de Oliveira and ter Steege (2015), to investigate the variation within the story structure of the forest. ~~At each height level, six WC, two temperature, and two light sensors (except for 1.5 m with only one light sensor) were installed in/on top of different bryophyte communities located on an approximately 26 m high tree (Fig. S2, Table S1).~~ It needs to be mentioned, that not only one single species was measured by one sensor, but usually several bryophyte species and also other cryptogams, such as lichenized and non-lichenized fungi and algae, as well as heterotrophic fungi, bacteria and archaea, which grow together forming a cryptogamic community. Thus, the organisms mentioned throughout this paper were the dominating but not solitarily living species. The restriction of the measurements to one individual tree needs to be considered, as a complete independence of the replicate sensors could not be assured. However, due to the large effort of such an installation within the rain forest, it was not possible to equip more trees with additional instruments. Thus, the data obtained from the measurements on this individual tree should be considered as exemplary. The WC sensors were placed in four different bryophyte communities being heterogeneously distributed along ~~the four~~ three height levels. At 1.5 m height, the WC sensors were installed in communities dominated by *Sematophyllum subsimplex* (5 sensors) and *Leucobryum martianum* (1 sensor), at 8 m in *Octoblepharum cocuiense* (~~3~~ 2 sensors) and *Symbiezidium barbiflorum* (~~3~~ 1 sensor~~s~~), ~~and at 18~~ and at 23 m in *Symbiezidium barbiflorum* (~~6~~ 3 sensors ~~at each height level~~; Fig. S2, Fig. S3). ~~A~~Additionally, at each height level~~,~~ ~~six WC,~~ two temperature~~,~~ and two light sensors (except for 1.5 m with only one light sensor) were installed in/on top of ~~different~~the bryophyte communities located on the~~an~~ approximately 26 m high tree (Fig. S2, Table S1). The temperature sensors were installed in the same communities ~~at each height~~as the WC sensors, and the light sensors were installed adjacent to them on ~ 5 cm long sticks (Fig. S1). As the morphology of the different species affects their overall WC, different maximum WC ~~and patterns of the drying process~~contents were observed (Tab. S1, S2). ~~The sensors were installed with the following orientations:~~ A~~a~~t 1.5 and 8 m the sensors were installed vertically along the trunk, ~~at 18 m at the upper side of a slightly sloped branch, and~~ whereas at 23 m they were placed at the upper side of a horizontal branch. Thus, also the orientation at the stem may influence the WC of the bryophyte communities, not only the species and the height above ground. Furthermore, sample properties as their thickness and density might play a relevant role for their WC, as samples at 1.5 m height tended to be more loose and thinner as compared to the ones at the upper height levels (Fig. S4). Since the installation, automatic measurements at 5-minute intervals were taken with a data logger (CR1000; Campbell Scientific, Logan, Utah, USA) equipped with a relay multiplexer (AM16/32; Campbell Scientific, Bremen, Germany) and two interfaces.

The WC sensors, initially developed for biological soil crust research (Tucker et al., 2017; Weber et al., 2016), were optimized for measurements in epiphytic bryophyte communities by a straight-lined construction and with outer pins of 25 mm length, serving as an effective holdfast. However, during stormy episodes and/or physical friction, some WC and temperature sensors fell out of the moss samples and required a reinstallation. Additionally, during some episodes the sensors showed unreliable data, which had to be removed from the overall dataset. All data, which could be used for data analysis, are shown in Fig. S5. ~~Accordingly, the WC sensor no. 6 (1.5 m) was repositioned in January 2015, WC sensor no. 1 (1.5 m) in November 2015, WC sensor no. 1, no. 6 to no. 24 and all temperature sensors in November 2016. The periods when the sensors were not installed in the bryophyte samples and data after total reinstallation in November 2016 were excluded from the data set.~~

The ~~WC~~ EC values were oscillating, causing an inaccuracy corresponding to approximately ~~15~~20 mV~~% dry weight (DW)~~. Besides the specific position in the substrate, the E~~W~~C also depends on the texture of the sample material, its ion concentration, and the temperature. Because of all these factors influencing the sensor readings, the provided values of the WC should be considered as the best possible estimates and not as exact values. For the temperature measurements, thermocouples (Conatex, St. Wendel, Germany) with a tip length of 80 mm and a measurement accuracy of ± 0.5 °C were used. For the light sensors, GaAsP-photodiodes (G1118, Hamamatsu Photonics Deutschland GmbH, Herrsching, Germany) were placed in a housing covered by a convex translucent polytetrafluoroethylene (PTFE) cap and calibrated against a PAR (photosynthetically active radiation) quantum sensor (SKP215; Skye Instruments, Llandrindod Wells, Powys, UK).

The average daily PAR values were calculated from the data collected during daytime, i.e., 6:00 to 18:00, while $\mathrm{PAR}_{\max}$ represents the daily maximum value. The values obtained from the light sensors fluctuated by approximately ± 10 μmol m^{-2} s^{-1} photosynthetic photon flux density (PPFD)~~, thus an averaging of 30-minute intervals allowed a smoothening of the data~~ ~~(Fig. S5)~~. ~~The smoothened data were used for detailed illustrations of seasonal variability (Fig. 2 and S6), whereas the 5-minute data were used for calculations in order to also consider short light fleck events~~ ~~Furthermore, from all parameters~~ To smoothen the microclimate data, 30-minute averages were calculated and used for all further calculations. During measurements, the light sensors were regularly checked for algal growth and cleaned accordingly.

2.3 Calculation of the water content (WC)

The WC sensors measure the electrical conductivity in the field (EC_t), which is influenced by temperature; consequently, a temperature correction was performed according to Eq. (1), analogous to Weber et al. (2016):

$$EC_{25} = f_T * EC_{t}, \quad (1)$$

with EC_{25} as EC at 25 °C, T as bryophyte temperature [°C] and the temperature conversion factor f_T:

$$f_T = 0.447 + 1.4034\, e^{-T/26.815}. \quad (2)$$

The WC sensor has a fixed distance between the sensor pins, which ensures that in all sensors the resistance is equal. This guarantees that the electrical voltage, being the inverse resistance, is proportional to the electrical conductivity. The values of the sensors were recorded as electrical voltage in mV and by calibration transformed into the WC of the samples, ~~which is~~ given as dry weight percentage, as explained below ~~(% DW)~~.

~~A calibration was conducted for~~To determine the maximum water content of the different bryophyte communities ~~all the communities dominated by different bryophyte species. For this~~, samples of them were collected in the forest area surrounding the ATTO site. They were removed from the stem with a pocket knife and stored in paper bags in an air conditioned lab container until calibration (few hours after collection). Prior to the calibration, the samples were cleaned from adhering material using forceps. The weight of the bryophytes was determined when they were moistened until saturation (temperature 30° C, RH 100 %) and again after drying in a dryer overnight (temperature 40° C, RH 30 %) to simulate the natural range of the WC under controlled temperature and RH conditions. The dry weight (DW) was determined after drying at 60° C until weight consistency was reached (Caesar et al., 2018). The WC of the sample was calculated according to the formula in Weber et al. (2016):

$$WC\ [\%\ DW] = \frac{(FW - DW)}{DW} * 100\ \%, \qquad (3)$$

with FW as sample fresh weight [g] and DW as sample dry weight [g].

In a previous approach, calibration curves were established under controlled conditions, logging the electrical conductivity values and the corresponding weight/water content of samples of the different bryophyte species during drying, analogous to (Weber et al., 2016). However, the variability of electrical conductivity values between samples and even at different spots within one sample turned out to be too large and thus this was not a feasible approach to calibrate the sensors. On the other hand, the electrical conductivity values decreased in a linear way with decreasing sample weight, demonstrating that a linear relationship between both factors could be assumed (except for water contents close to saturation).

In the current approach, the calibration of the water content was performed, based on the maximum and minimum values of electrical conductivity reached in the field and the ~~amplitude~~ maximum ~~of the~~ WCs reached during the laboratory measurements. We assumed, that the maximum electrical conductivity achieved in the field corresponds to the maximum WC achieved in the laboratory, due to water saturation of the samples during the laboratory measurement. The minimum electrical conductivity corresponds to a water content of 0%, as we assumed that all samples dried at least once over the whole measurement period~~water contents after overnight drying, as we are confident that this happened at least a few times during the dry season of the year~~.

~~As we got the impression that electrical conductivity values may contain some outliers in the upper data range, we reduced the electrical conductivity data by the uppermost and lowermost 0.1% of the data points (Tab. S3, Fig. S7)~~. Accordingly, the water content (WC) was calculated as follows:

$$WC\ [\%\ DW] = \frac{\cancel{(EC_i - E}WC_{max\cancel{perc\ 0.1}})}{(EC_{\cancel{perc\ 99.9}max} - EC_{\cancel{perc\ 0.1}min})} * (\cancel{W}EC_{\cancel{imax}} - \cancel{W}EC_{min}), \qquad (4)$$

with WC_{max} corresponding to the maximum WC measured in the laboratory, EC_i as electrical conductivity, $EC_{min\cancel{perc\ 0.1}}$ as the minimum electrical conductivity ~~after subtraction of the lower 0.1% of the values~~, and $EC_{max\cancel{perc\ 99.9}}$ as the maximum electrical conductivity ~~after subtraction of the upper 0.1% of the values~~ measured in the field. ~~WC_{max} corresponds to the maximum WC and WC_{min} to the minimum WC (after overnight drying at 40°C and 30% air humidity) measured in the laboratory.~~

The measured electrical conductivity values showed short-time oscillations, which might be caused by the fact that the bryophytes cushions have some air spaces in-between, as we observed that these oscillations are less pronounced in denser substrate. Nevertheless, the overall functionality of the sensors is still ensured also in less dense material, and the short-term fluctuations could be removed with a 30-minute smoothing algorithm ~~(Fig. S5)~~. Thus, for all calculations the 30-minute averages were ~~considered~~used.~~, except for the estimates of physiological activity~~.

~~The smoothened data were used for figures and calculations as stated in section 2.2.~~ The electrical conductivity data of replicate samples at the same height ~~and of the same division (moss versus liverwort)~~ were combined to obtain average values for each height.

2.4 Meteorology

For the purpose of long-term monitoring, a set of meteorological parameters is being measured within the ATTO project since 2012. In our study we used rainfall data measured at 81 m [mm min^{-1}] (Rain gauge TB4, Hydrological Services Pty. Ltd., Australia), relative humidity (RH) measured at 26 m [%], air temperature measured at 26 m [°C] (Termohygrometer CS215, Rotronic Measurement Solutions,UK), and photosynthetically active radiation (PAR) measured at 75 m height above the ground [µmol $\text{m}^{-2}\,\text{s}^{-1}$ PPFD] (Quantum sensor PAR LITE, Kipp & Zonen, Netherlands). All data were recorded at 1-minute intervals with data loggers (CR3000 and CR1000, Campbell Scientific, Logan, Utah, USA) on the walk-up tower (Andreae et al., 2015).

For calculation of the average light intensities per month, season or year (PAR_{avg} month, PAR_{avg} season, PAR_{avg} year) only values during daytime (6:00 – 18:00 local time) were considered. Rainfall data are presented as accumulated values in millimeters per month, season, or year, which were calculated by an integration of 30~~5~~-minute intervals. As there were gaps in the data record of the rain detection, additional information from the WC sensors were used to calculate the number of days with rain events. The sensors at 1.5 m height were found to react reliably to rain events. Thus, the gaps in the rain detection were corrected with the information received from these sensors. Furthermore, the amount of rain within each month was corrected by assuming that during the missing days there were the same amounts as during the rest of the month. Overall, a malfunction of the rain detection was observed on only 6 % of the days (Table S4).

The information on fog events was provided by visibility measurements using an optical fog sensor installed at 50 m height (OFS, Eigenbrodt GmbH, Königsmoor, Germany). Fog was defined to occur at visibility values below 2,000 m.

Based on the climate data, we calculated the dew point temperature, at which saturated air humidity levels are reached. If the temperature drops below the dew point, condensation might occur and form liquid water. The dew point spread is the temperature difference between a surface temperature and the dew point of the surrounding air and can be used to assess potential condensation processes at surfaces. If the difference between the surface temperature T_s and the dew point of the surrounding air T_d is negative, water vapor is able to condense at the colder surface. The calculations were performed according to the following equations:

$$\Delta T_d = T_s - T_d \qquad (5)$$

and

$$T_d = \frac{241.2\ \ln\left(\frac{\varphi}{100}\right) + \frac{4222.03716\,\vartheta}{241.2 + \vartheta}}{17.5043 - \ln\left(\frac{\varphi}{100}\right) - \frac{17.5043}{241.2 + \vartheta}} \qquad (6)$$

With ΔT_d = dew point spread [°C], T_s = surface temperature (bryophyte sensors, 23 m or 1.5 m) [°C], T_d = dew point temperature air [°C], ϑ = temperature [°C], φ = relative humidity [%]. The dew point spread calculation was performed for the levels of 23 m and 1.5 m height. As a data source for air temperature and humidity, meteorology data assessed at the walk-up tower at 26 m and 1.5 m were used. For surface temperature (T_s), the temperature data measured within the bryophyte communities at 23 m and 1.5 m height were applied. The dew point calculations were performed with R version 3.6.1 (2019-07-05).

Time readings are always presented as UTC (universal coordinated time) values, except for diurnal cycles, where local time (LT, i.e., UTC-4) is shown, as labeled in the figures.

2.5 Potential physiological activity of bryophytes

The physiological activity of bryophytes – and of cryptogams in general – is primarily controlled by water and light, whereas temperature plays a secondary role, at least in the environment of the central Amazon (Lösch et al., 1994; Wagner et al., 2013). While the availability of water determines the overall time of physiological activity, the light intensity regulates whether net photosynthesis (NP) or dark respiration (DR) dominates the overall metabolic balance. Furthermore, high nighttime temperatures cause increased carbon losses due to high respiration rates, as previously shown for lichens (Lange et al., 1998, 2000). For tropical bryophytes along an altitudinal gradient in Panama, however, it has been shown that respiration loss during the night might not play the determining role for an overall positive net carbon balance, as species acclimatized to elevated temperatures, but that the restricted time for photosynthesis was a decisive factor (Wagner et al., 2013).

To assess the potential physiological activity of bryophyte communities, the water and light conditions as major drivers of the metabolism were investigated in somewhat greater detail. The lower water compensation point (WCP) presents the minimum WC that allows positive net photosynthesis. For the tropical liverwort *Symbiezidium* spp., occurring in the lowlands near sea level in Panama, WCP values in the range between ~ 30 and ~ 80 % have been determined (Wagner et al., 2013) (Table ~~S5~~S4).

The lower light compensation point ($\mathrm{LCP_l}$) represents the minimum light intensity that allows a positive primary production; it ranges between ~ 3 and ~ 12 µmol m^{-2} s^{-1} for bryophytes (based on measurements of *Ectropothecicum* cf. *perrotii, Frullania* spec, *Neckera* spec., *Plagiochila divergens, Plagiochila squamulosa, Porothamnium stipiatum, Porotrichum molliculum, Racopilum tomentosum, Radula boryana, Rhizogonium spiniforme*) occurring in African tropical lowland rain forests (Lösch et al., 1994). The epiphytic bryophytes grew in an upper lowland rain forest in the Kahuzi-Biega National Park (Zaire) at about 800 m a. s. l.. Microclimatic conditions inside the forest were similar to the conditions at the ATTO site, as RH ranged around 60–~~-~~70 % during sunny days and temperatures remained above 20 °C during night and day. At light intensities below the $\mathrm{LCP_l}$ and WCs below the WCP, respiration rates are higher than NP rates, causing overall net respiration to occur.

With regard to temperature, a range for optimum NP (T_{opt}) and an upper compensation point, where NP equals DR (TCP) can be defined. For tropical bryophytes (i. e., the species *Octoblepharum pulvinatum, Orthostichopsis tetragona, Plagiochila* sp. 1, *Stictolejeunea squamata, Symbiezidium* spp., *Zelometeorium patulum*), T_{opt} ranges between 24 and 27 °C and the TCP ranges between 30 and 36 °C, as described by Wagner and coauthors (Wagner et al., 2013). For long-term survival and growth, the bryophytes need to be predominantly exposed to temperatures below the upper compensation point, at least under humid conditions. The measurements performed by Wagner et al. (2013) were conducted at a study site (BT) in a lowland rainforest in Western Panama on the Bocas del Toro archipelago, located approximately at sea level. The mean temperature was 25 °C (26 °C during day, 24 °C during night), thus slightly warmer than the temperatures measured at ATTO. With 3,300 mm a^{-1} of rain, BT is in a similar range as the ATTO site (2,540 mm a^{-1}). Unfortunately, literature data on the compensation points are rare, facilitating only a first approximate assessment of the physiological processes (Lösch et al., 1994; Wagner et al., 2013). A WC above the compensation point allows NP if both light intensity and temperature are above the lower compensation point. If WCs are above the compensation point but light intensities are too low, or if temperatures are above the upper compensation point, net DR occurs. There is also a narrow span of low WCs, when samples are activated already but despite sufficient light intensities only net respiration can be measured. As this span of WCs is narrow and respiration rates are low, it has been neglected in the current calculations. The compensation points for the different parameters are also to some extent interrelated, e.g., the water compensation point of lichens has been shown to slightly increase with increasing temperature (Lange, 1980), but this can be neglected in such a first qualitative approach. Finally, also inter- and intraspecific variation of compensation points could not be considered in the current study.

2.6 Data analysis

All data processing steps and analyses were performed with the software IGOR Pro (Igor Pro 6.37, WaveMetrics. Inc, Lake Oswego, Oregon, USA). For the average values obtained at the different height levels, the data of the individual sensors were pooled.

3 Results

3.1 Microclimatic conditions

3.1.1 Annual fluctuation of monthly mean values

Over the course of the two years of measurements, the monthly mean values of the WC, temperature, and light conditions experienced by the epiphytic bryophyte communities, as well as the above-canopy meteorological conditions, varied between seasons and years. Comparing the two consecutive years, the effect of an El Niño event was clearly detectable, as rainfall amounts were 35 % lower (525 mm versus 805 mm) and relative air humidity 11 % lower (81 % versus 92 %) between October 2015 and February 2016 as compared to the same time-span in the previous year (Fig. 1, Table ~~S4~~S3).

The monthly mean values of above-canopy PAR (PAR$_{avg}$) were rather stable throughout the years and did not differ between the years 2015 and 2016, ranging between 635 and 1150 µmol m^{-2} s^{-1} during the daytime (Fig. 1, Table S3~~1a~~). The PAR$_{avg}$ values in the understory at 1.5 m also showed only minor seasonal variation, whereas those at higher levels revealed larger variations (Fig. 1~~2~~, Table~~Fig~~. S5~~6~~). However, the light conditions observed at one individual tree are strongly influenced by its canopy structure and foliation and thus could not be considered as data representative for the canopy in general.

Over the course of the years, the monthly mean temperatures at all heights as well as above-canopy temperatures showed a parallel behavior (Fig. 1). The temperatures decreased in a stepwise manner from the canopy to the understory, and temperatures within bryophytes at 23 m height were frequently higher than the temperatures measured above the canopy (Fig. 1, ~~Table 1a,~~ Fig. ~~S8~~S7). Overall, temperatures at all height levels were lower and more similar during the wet than the dry seasons.

Over the course of the years, the monthly WCs of epiphytic bryophytes showed similar patterns corresponding to the increasing and decreasing values of rain and RH. During the dry season 2015, it rained on 25 % of the days, while in the previous and subsequent years rain occurred at a higher frequency (58 % and 31 % of the days, respectively; Fig. 1, Table ~~S4~~S3). Monthly rain amounts varied from 9 mm during the dry to 341 mm during the wet season. In 2016, the rain increased from January to March and decreased from March to August, while in 2015 the monthly rain amounts were more variable but still lower throughout the year. The lowest monthly average of the RH was observed during the dry season 2015 with 74 ± 15 %. The monthly WC values of epiphytic bryophyte communities at 1.5 and 8 m varied between seasons in parallel to the monthly rain amounts, whereas~~ the highest~~ at 23 m the values remained relatively stable over the complete measurement time~~, followed by those at 18 m~~. During the dry seasons, the WC~~s~~ of the mosses at 1.5 m tended to be lowest, whereas during the wet season this was the case for the ~~and~~ liverworts at ~~8~~ 23 m ~~tended to be the lowest, whereas during the wet seasons the liverworts at 8 m height had the lowest values~~height (Fig. 1, Tab. 2). ~~For most of the height zones the highest monthly averages of the WC values were reached from January to May 2015 and from February to April 2016, whereas the lowest contents were measured from September 2015 to January 2016. The mosses at 8 m height showed rather high WCs during dry season 2015, and these samples showed only a slight alternation between the seasons. Furthermore, the liverworts at 8, 18, and 23 m height showed particularly high conductivity values in November and December 2016, which might be caused by a previously required reinstallation. Consequently, the calculated WC values of the reinstalled sensors need to be considered with special care, as they cannot be directly compared to the values prior to reinstallation.~~

3.1.2 Seasonal changes between wet and dry season

The wet seasons were characterized by a high frequency of precipitation events, large amounts of rain per event, the frequent appearance of fog, and high RH values, ranging mostly above 70 % (Fig. 2, Table 2~~Fig. 3~~, Fig. S6). In contrast, during the dry season the precipitation events were much rarer and smaller, there was hardly any occurrence of fog, and the RH regularly had values below 60 %~~ (Fig. 2, Fig. 3, Fig. S6)~~. Comparing environmental conditions of the seasons, the diel amplitudes of ambient light, temperature, and RH were larger in the dry compared to the wet season (Fig. 3). While the microclimatic temperature and light conditions within and on top of the epiphytic bryophyte communities mostly followed the above-canopy conditions, modified by canopy shading, the WC of bryophytes did not present a clear pattern (Fig. 3).

The above-canopy light intensity (PAR$_{avg}$ daytime) tended to be higher and to show somewhat stronger fluctuations in the dry season than in the wet season (~~970~~ 950 ± ~~650~~ 93 µmol m^{-2} s^{-1} vs. ~~740~~ 738 ± ~~570~~ 46 µmol m^{-2} s^{-1};~~) (~~Table 2). During both main seasons the average light intensity (PAR$_{avg}$ daytime) decreased from the canopy towards the understory. During the dry season this happened in a regular stepwise manner, whereas in the wet season there were some irregularities, probably caused by the local canopy structure (Fig. 2, 3 Table 2).

The temperatures showed a decreasing gradient from the canopy (wet season: 25.~~3~~ 7 ± ~~2.0~~0.7 °C, dry season: 27.2± ~~3.5~~1.0 °C) towards the understory (wet season: 24.9 ± ~~1.0~~0.4 °C, dry season: ~~25.5~~26.0± ~~1.7~~0.8 °C) and the differences among heights and diel amplitudes were more pronounced during the dry season (Fig. 2, 3, Table 2). During the dry season, temperatures ~~At 23 m height, temperatures~~ within the bryophyte communities at 23 m height were frequently higher than the above-canopy values, and ~~during the dry season~~ even the seasonal average temperature was 0.6~~5~~°C higher, probably due to surface heating (Table 2).

During the wet seasons of 2015 and 2016, rain occurred on average on 84 % of the days and in the dry season on 28 % of the days (Table S3). During the wet season, an average RH of ~~95~~ 94 ± ~~9~~ 2 % and frequently even full saturation was reached, while during the dry season the RH reached an average value of ~~87~~ 84 ± ~~14~~ 6 % (Table 2). Fog was recorded on 60 % of the days during the wet seasons and on 20 % of the days during the dry seasons, respectively (Fig. 2, Table S3). According to our observations, fog observed above the canopy normally also occurred (at least to some extent) within the forest.

The WC of the ~~mosses~~ bryophytes at 1.5 and 8 m ~~and the liverworts at 18 m height~~ responded consistently to rain events, while for the liverworts at ~~8 and~~ 23 m height ~~not in all cases~~only sometimes an immediate response was observed. During the wet season, the ~~mosses~~ bryophytes at 1.5 and 8 m height ~~indicated~~ contained an increased WC over several days after a rain event, while in the dry season ~~they had lower WC values~~the samples tended to dry quickly again. Overall, the ~~liverworts~~ bryophytes at 8 m and 23 m showed a regular and pronounced nightly increase of the WC, especially during the dry season (Fig. 2~~, Fig. S6~~). ~~The WC of the liverworts at 18 m showed a large variation during the dry season in 2016, which was most probably caused by the repositioning in November~~

~~2016.~~ Nightly condensation ~~fog~~ might serve as an additional source of water, as in ~50 % of the wet season and ~30% of the dry season days ~~some cases~~ the surface temperatures of the bryophytes at 23 m height went below the calculated dew point temperature (Fig. S8, Fig. S9). Contrastingly, at 1.5 m height dew point temperatures were only surpassed during ~9 % of the days, independently of season. This occurred preferably in the early morning hours and lasted for ~ 2 h in the canopy (23 m), but only ~ 1 h in the understory (1.5 m).

3.2 Potential physiological activity of bryophytes

Whereas overall light intensities at the upper ~~three~~ two height levels were rather similar, with values below 108~~,~~ ~~138,~~ and 147 µmol m^{-2} s^{-1} (at 8~~,~~ ~~18,~~ and 23 m height) in 90 % of the time, the values at 1.5 m height remained below 10 µmol m^{-2} s^{-1} during the same time fraction (Fig. 4). In contrast to that, maximum light intensities were relatively similar high, reaching 1,550 (1.5 m), 1,500 (8 m), 1,040 (18 m), and 950 µmol m^{-2} s^{-1} (23 m) ~~(Fig. 4)~~. ~~In the understory (1.5 m),~~ ~~I~~if we assume ~~the~~ a lower light compensation point (LCP$_l$)~~,~~ ranging between 3 and 12 µmol m^{-2} s^{-1} (Lösch et al., 1994), the understory samples (1.5 m) ~~was~~ exceeded that range only in less than 20 % ~~in 2-19 %~~ of the time during both the wet and the dry season. ~~-during the wet season and in 4-16 % of the time during the dry season~~, whereas at the ~~two~~ uppermost height level~~s~~ the bryophytes exceeded these values in ~~34-47 %~~during one third to almost half of the time ~~during both seasons~~ (Table 3).

The temperatures inside the moss stands at different height levels mainly ranged between 22~~3.0~~ °C and ~~33~~~28~~.0~~ °C during the wet and between 23 °C and ~33 °C during the dry season ~~at different height levels within the canopy~~ (Fig. 4). ~~In~~ For tropical lowland regions, the optimum temperatures for bryophytes (T$_{opt}$) have been suggested to range between 24.0 °C and 27.0 °C (Wagner et al., 2013). ~~In our studies~~If we assume this range for our study, the temperatures in the understory remained within ~~this range~~these limits in 2-77 -% of the time during the wet season and in 9-60 % of the time during the dry season (Table 3). In the canopy, temperatures remained in this range in 4-54 % of the time during the wet and in 6-~~34~~ 35 % of the time during the dry season (Table 3). For an ~~In the understory, the~~ upper temperature compensation point (TCP) ~~of 30.0 °C – 36.0 °C (Wagner et al., 2013)~~, above which respiration exceeds photosynthesis, Wagner and co-authors suggested 30.0 °C – 36.0 °C (Wagner et al., 2013). In the understory, this TCP was never surpassed during the wet season and only ~~in 0 – 3~~ 4 ~~% of the time~~rarely during the dry season. Similarly, at the uppermost canopy level the upper TCP was surpassed in 0-3 % of the time during the wet and in ~~3-26~~0-27 % of the time during the dry season. Overall, the highest temperatures were reached when the bryophytes were relatively dry and most probably inactive (Fig. S10).

The WC of bryophytes differed along the vertical profile, with ~~higher values reached~~smaller values in the ~~canopy~~ understory at 1.5 m height~~(18 and 23 m)~~ than in the ~~understory~~canopy (8 m and 23 m), particularly during the dry season (Fig. 4) ~~(1.5 and 8 m)~~. Considering ~~as reference, T~~t~~he~~a lower water compensation point (WCP)~~, ranging~~ between 30 and 80 % according to the literature (Wagner et al., 2013), bryophytes at the uppermost level~~t~~ surpassed these values during 3~~0~~-80% of the time during the wet and 6-64 % of the time during the dry season. Contrastingly, at 1.5 m and 8 m height there were larger differences between seasons, as the assumed upper range of the WCP was only rarely reached during the dry but during ~ 40% of the time during the wet season. ~~his range was surpassed by the bryophytes mosses (1.5 and, 8 m and 23 m) in 53 – 100 % of the time during the wet and in 4-98 % of the time during the dry seasonin almost 100% of the time for both seasons. The liverworts at 8 m height exceeded this value in 18-98 % of the time during the wet and in 5-86 % of the time during the dry season. At the uppermost two height levels, the liverworts showed no difference of this rate for both seasons, surpassing the WCP in 93-100 % of the time~~ (Fig. 4; Table 3).

4 Discussion

4.1 Microclimatic conditions

In the current study we measured the microclimatic conditions experienced by epiphytic bryophyte communities ~~at different height levels in~~along a vertical gradient ~~at the Amazon rainforest~~ over the course of more than two years. In previous studies, ~~such~~ microclimatic data on the light, temperature, and air humidity ~~data~~ have been assessed ~~,~~at different height levels within the forest ~~only over short time-spans of hours or days, but separately for radiation, photosynthetically activity, light, temperature, humidity, CO_2 influence, compensation points, gas exchange at the canopy of forest environments~~ (Chazdon and Fetcher, 1984; Lösch et al., 1994; Romero et al., 2006), but long-term measurements of the water content and the light and temperature on top and inside the cryptogamic communities and have been missing up to now.

The microclimatic conditions experienced by epiphytic bryophyte communities along a height gradient at the ATTO site followed the meteorological parameters to some extent, but they also revealed microsite-specific properties regarding annual, seasonal, and diel microclimate patterns. Whereas the water content and the temperature mostly followed the patterns of the meteorological parameters precipitation and temperature, the light intensities were clearly altered, particularly in the understory, due to the local canopy structure.

Within one height level, the small-scale environmental conditions, such as radiation and shading, water conditions, and wind velocity vary, depending on the specific habitat conditions, as e.g. exposition, tree foliage and inclination of the substrate (Barkman, 1958; Campos et al., 2019; Cornelissen and ter Steege, 1989; Oliveira and Oliveira, 2016; Sierra et al., 2018). These small-scale patterns also explain the variability observed within one height level.

Over the ~~course of two years~~measurement period, the monthly averages of above-canopy light conditions (PAR_{avg}) were rather stable (Fig. 1, Table ~~S4~~S3). Within the canopy, the monthly PAR_{avg} values at 23 m height tended to be higher during the dry seasons, whereas patterns were less clear at ~~18 and~~ 8 m height and there was hardly any seasonal variation at 1.5 m height. This was most probably an effect of the canopy structure, cushion orientation, and shading. The sensors at 1.5 and 8 m were installed vertically along the trunk, ~~at 18 m height they were placed on the upper side of a slightly sloped branch, and~~ whereas at 23 m they were positioned on the upper side of a horizontal branch. As the light sensors at 23 m height were located within the canopy, newly growing leaves may have periodically shaded the organisms, which may explain the lower monthly PAR$_{avg}$ values at this height level compared to the values at the lower levels, where sunbeams could come through the canopy of neighboring trees and open space.

The diel patterns of PAR$_{avg}$ are expected to show a decreasing gradient from the canopy to the understory, as the canopy receives most solar radiation, while the understory vegetation is expected to be shaded by foliage and branches. During the dry season this general pattern was indeed observed, whereas during the wet season mean light intensities were often higher at 8 than at ~~18 and~~ 23 m, probably also caused by canopy shading effects at the upper two height levels (Fig. 2). High light intensities above 1000 µmol s^{-2} s^{-1} occurred in the understory only as small light spots of short duration and thus were only observed in 0.008 % of the time. For the understory of a rain forest in Costa Rica, light intensities were reported to range from 10 to 1000 µmol m^{-2} s^{-1}, and more than in 50 % of the total amount of light resulted from sun flecks (Chazdon and Fetcher, 1984). Bryophyte and lichen taxa in the understory are known to be adapted to these low light conditions and are able to make efficient use of the rather short periods of high light intensities (Lakatos et al., 2006; Lange et al., 2000; Wagner et al., 2014).

The temperatures measured inside the bryophyte communities followed the above-canopy temperature at all height levels, with a mostly increasing gradient from the understory towards the canopy, probably caused by a reduced shading effect towards the canopy (Fig. 1, Table~~.~~ 1, ~~Tab.~~ 2). At the uppermost height level, mean temperatures inside the bryophyte communities often were even higher than the mean above-canopy temperatures. During the wet season, the overall temperature conditions were more buffered due to reduced incoming radiation caused by clouds and a frequent mixing of the air masses during rain events (von Arx et al., 2012; Gaudio et al., 2017; Thompson and Pinker, 1975).

The microclimatic mean temperature differences measured inside the bryophyte stands between the understory (1.5 m) and the canopy (23 m) were 1.5 °C in the dry and only 0.5 °C in the wet season. Compared to these results, a temperature difference of 4.0 °C was determined during the dry season in a tropical evergreen forest in Thailand, while in the wet season it was below 1.0 °C, thus corresponding quite well to our results (Thompson and Pinker, 1975) (Table 2). The daily amplitude of the temperature was about twice as large in the canopy as compared to the understory (Fig. 3~~.~~) This could be caused by the exposure to strong solar radiation and higher wind velocity in the canopy compared to the sheltered understory (Kruijt et al., 2000).

Rainfall amounts and relative air humidity values differed between the seasons and also between the years, as they were considerably higher between October 2014 and February 2015 as compared to the following year. This was most probably to an El Niño event, which caused air humidity and WC of bryophytes to be substantially lower compared to the previous dry season (Fig. 1, Table 1). Generally, the moisture conditions, including rain, fog, and RH, differed between seasons, resulting in different WC patterns of bryophytes. A higher frequency of rain during the wet season particularly affected the ~~moss~~ bryophyte communities at the lower levels (1.5 and 8 m), whereas those in the canopy showed similar water contents during all seasons~~;~~ (Fig. 2, Fig. S6a, Table 2). ~~At the same time the higher RH and the more frequent occurrence of fog tended to result somewhat higher WC values of the bryophytes during the wet season as compared to the dry season (Fig. 2, Table 2).~~

The data also suggest that the position of the measured communities and the tree foliage~~angle of the stem or branch colonized by the investigated bryophytes~~ played a crucial role for rainwater absorption and the subsequent drying process. Whereas the sensors at 1.5 m and 8 m height responded quite reliably to rain events during all seasons, these at 23 m responded quite reliably during the dry but only rarely during the wet seasons. This might be caused by a dense foliage during the wet season, shading the communities at 23 m from direct inundation, whereas during the dry season the canopy foliage changes a lot and intense leave shedding takes place before new leaves develop, which seems to allow rain to also reach the samples directly below the canopy (Lopes et al., 2016). ~~The bryophytes at 1.5 and 8 m height were oriented vertically, those at 18 m were placed on the upper side of a slightly sloping branch, and those at 23 m were located on the upper side of a nearly horizontally oriented branch. Long-term climate data have shown that the winds during the wet season predominantly originated from north and north-eastern directions, while during the dry season south- and south-easterly winds prevailed (Pöhlker et al., 2019). At 8 m height, the investigated bryophytes were exposed to the west, and thus were only sometimes directly influenced by precipitation. Also at 23 m height the bryophytes did not always show a clear response to precipitation events, although they were oriented horizontally on a branch (Fig. 2, Fig. S4, Fig. S6). Here, also the tree foliation and epiphytic vascular plants might have shielded the sensors from direct precipitation during the wet season.~~

During the wet season, the WC of bryophytes in the understory and at 8 m height responded strongly to rain events and subsequently, the water was lost gradually with bryophytes staying wet and active over prolonged time spans, indicating that large amounts of water were taken up during prolonged rain events (Fig. 2, Fig. S6). In contrast to that, d~~D~~uring the dry season~~,~~ the drying of the samples ~~located in the canopy~~ occurred quite rapidly after the rain during the dry season. Most rain events in the Central Amazon occur in the early afternoon (12:00–14:00 LT) and more than 75 % of them are weak events of less than 10 mm (Cuartas et al., 2007), which often cause no complete water saturation of the bryophytes. Consequently, the organisms tend to dry much quicker than after~~ a~~ strong rain events occurring more frequently during the wet season~~ that causes full saturation of the community~~. ~~Besides the solar radiation, probably also the higher wind velocities accelerated the desiccation of the epiphytic cryptogams in the canopy (Oliver, 1971). During the dry season, the diel above-canopy RH amplitudes were larger and reached lower values, thus also promoting quicker drying of bryophyte samples.~~

In a rain forest environment, condensation and stemflow water need to be considered as potential additional sources of water for epiphytic covers as well as for near-stem vegetation at the forest floor (Lakatos et al., 2012; van Stan and Gordon, 2018). It has been estimated that in tropical forests the stemflow water could provide up to 4 % of the annual rainfall amount (Lloyd and Marques F, 1988; Marin et al., 2000; van Stan and Gordon, 2018), corresponding to maximum values of 68 and 75 mm in the years 2015 and 2016 at the ATTO site. The water content data at

8 m and 23 m height showed diel fluctuations, particularly during the dry season, with the highest water contents reached during the morning hours. This might be caused by condensation, as our data suggest that at 23 m height bryophyte temperatures regularly fall below dew point temperatures in the early morning hours. The WC of bryophytes could increase upon fog, which has also been shown in some other studies (León-Vargas et al., 2006). ~~The relevance of the~~In addition, also the water holding capacity ~~for the water content~~ of different bryophyte species, which is influenced by the life form and has ~~already~~ been described in several other studies (Lakatos et al., 2006; Romero et al., 2006; Williams and Flanagan, 1996; Proctor, 1990), may play a role in the WC patterns observed by us. At 23 m height, the WC sensors were placed in communities dominated by the liverwort *Symbiezidium barbiflorum* (Lejeuneaceae), which has been described to have the life-form of a mat (Batista and Santos, 2016; Mägdefrau, 1982; Valente et al., 2017). Mats have been described to have a high capillarity retention of water, which may support an uptake and particularly storage of condensed water. In addition, mats have an increased drought-tolerance, being more adapted to dry conditions as well as to extreme changes (Gimingham and Birse, 1957), which occur below the canopy as observed by us. In the understory at 1.5 m height, *Sematophyllum subsimplex* (Sematophyllaceae) and *Leucobryum martianum* (Dicranaceae) occur, which belong to the life-forms of wefts and turfs, respectively (Mägdefrau, 1982, Batista and Santos, 2016; Valente et al., 2017). They have been described to show high values of capillary water conduction and lower values of water retention (Mägdefrau, 1982). Wefts have been characterized as life forms characteristic of humidity areas (Gimingham and Birse, 1957). ~~The WC of bryophytes in the understory responded clearly to rain events during the wet season (Fig. 3a), and subsequently water was lost gradually indicating that large amounts of water were taken up during prolonged rain events, which were subsequently lost again rather gradually, with bryophytes staying wet and active over prolonged time spans (Fig. 2, Fig. S6). The high WC of the bryophyte samples in the canopy can be explained by the higher water holding capacity of the liverwort *Symbiezidium*, which dominated in the canopy, and by its growth on inclined or vertical stems, where water drainage is less effective as compared to the vertical stem at the lower two levels.~~

The~~at~~ distribution of bryophytes among height zones exhibit a well-known pattern for the Amazon rainforest (Cornelissen and ter Steege, 1989; Mota de Oliveira, 2010; Mota de Oliveira and ter Steege, 2015; Pantoja et al., 2015). Studies describe that Lejeuneaceae (common liverwort family registered for Amazonian region) are more diverse and abundant~~, has a greater number of species and abundance~~ in the canopy area, while mosses are mainly concentrated at the tree base and trunk in a plateau ecosystem (Campos et al., 2019; Mota de Oliveira, 2010, 2018). The~~se~~ species identified by us (Table S1) have also been reported as being frequent at other tropical rain forest sites (Campos et al., 2015; Dislich et al., 2018; Gradstein and Salazar Allen, 1992; Mota de Oliveira et al., 2009; Pinheiro da Costa, 1999).

~~The relevance of the water holding capacity for the water content of different bryophyte species has already been described in several other studies (Lakatos et al., 2006; Romero et al., 2006; Williams and Flanagan, 1996). Based on life form, *Leucobryum martianum* (Dicranaceae) and *Octoblepharum cocuiense* (Calymperaceae) can be assigned as turf, *Sematophyllum subsimplex* (Sematophyllaceae) as weft and *Symbiezidium barbiflorum* (Lejeuneaceae) as mat (Batista and Santos, 2016; Valente et al., 2017). Those forms determine the storage capacity and water loss rate, whereas prevails the capillarity conduction or retention (Proctor, 1990). As a result, lower values of WC can be associated with turf life form due to their shoots with larger crowded leaves, dense foliage and the frequently occurring weft rhizoid, showing particularly high values for capillary water conduction, i.e., lower values of water retention. The opposite occurs with wefts and mats, where the capillarity retention of water is higher (Mägdefrau, 1982). Thereby, mats developed an increased drought-tolerance, being more adapted to dry conditions as well as to extreme changes, whereas wefts are life forms characteristic of humidity areas (Gimingham and Birse, 1957).~~

~~The WC measurements for liverworts at 8, 18, and 23 m height were unexpectedly high in the end of 2016. This can be explained by a reinstallation of some sensors, which previously had fallen out of the moss cushions. Sensor displacement or complete removal from the bryophyte samples might have been caused by mechanical disturbance, like heavy rain events, movement of branches, growth of epiphytic vascular plants, or animal activity. A necessary reinstallation of the sensors unfortunately affected the measured values, as electrical conductivity values vary depending on the bryophyte sample properties. This variability of data, depending on the exact placement of the sensors, illustrates that calculated WCs could only be considered as approximate values. Furthermore, also the density and thickness of the investigated bryophyte sample is of high relevance. These are features, which are closely linked to the species, but also influenced by abiotic habitat conditions (Fig. S4).~~

4.2 Potential physiological activity of bryophytes

The microenvironmental conditions influence the WC of epiphytic bryophyte communities, but the ability to deal with these conditions differs among species (interspecific variability), being determined by morphological and physiological features. Apart from the interspecific variability, the performance of a single species under differing microenvironmental conditions can also be modulated by short-term acclimation and long-term adaption processes, with the latter being driven by environmental exposure, genetic variation among populations, and plasticity, as, e.g., shown for bryophytes and lichens (Cornelissen et al., 2007; Marks et al., 2019; Pardow et al., 2010). These aspects help to understand the occurrence of bryophytes under widely varying microclimatic conditions within the canopy. During our study, we measured the microenvironmental conditions of epiphytic bryophytes and observed bryophyte taxa to vary depending on these. Additionally, we estimated the potential ranges of physiological activity based on the compensation points for light, temperature, and WC, which have been reported from other studies in tropical forests (Lösch et al., 1994; Wagner et al., 2013).

~~Whereas at the stem bases close to the ground the moss species *Sematophyllum subsimplex*, *Octoblepharum cocuiense,* and *Leucobryum martianum* were dominating, the liverwort *Symbiezidium barbiflorum* was the main species occurring at higher levels along the tree stem. Regarding the morphological adaptations, mosses (*L. martianum, O. cocuiense* and *S. subsimplex*) present wrapping, imbricate and concave leaves, and widening of the nerve as potentially adaptive structures for desiccation (Mägdefrau, 1982; Oliveira and Oliveira, 2016). In contrast, liverworts (*S. barbiflorum*) have blackish or transparent squamae, and lobules that protect the photosynthetic tissue, the epidermal pores and vegetative reproduction, which allows them to grown under dry conditions. (Bastos, 2008). Those attributes classify the organisms into functional groups that can avoid desiccation or increase the tolerance to desiccation (Glime, 2007).~~

~~These species have also been reported as being frequent at other tropical rain forest sites (Campos et al., 2015; Dislich et al., 2018; Gradstein and Salazar Allen, 1992; Mota de Oliveira et al., 2009; Pinheiro da Costa, 1999).~~

In the canopy it is essential for the cryptogams to be adapted to high light conditions and UV radiation in order to avoid cell damage by radiation (Green et al., 2005; Pardow and Lakatos, 2013; Sinha and Häder, 2008; Westberg and Kärnefelt, 1998). As high light conditions mainly occur as short light flecks in the understory, the organisms need to react rapidly and efficiently to changing light conditions to reach overall positive net photosynthesis rates. Furthermore, understory mosses and lichens show higher rates of net photosynthesis at low light conditions as compared to canopy species (Kangas et al., 2014; Lakatos et al., 2006; Wagner et al., 2013). Epiphytic organisms growing under low-light conditions in the understory are also known to have lower LCP$_l$ values compared to the ones in the canopy, as documented for epiphytic lichens in French Guiana (Lakatos et al., 2006).

The temperature regulates the overall velocity of metabolic processes. While it has a strong impact on the respiration, the photosynthetic light reaction is by far less affected by it (Elbert et al., 2012; Green and Proctor, 2016; Lange et al., 1998). As the measured net photosynthesis rates are the sum of simultaneously occurring photosynthesis and respiration processes, positive net photosynthesis may still be reached at higher temperatures, if the photosynthetic capacity is high enough, whereas during the night, high temperatures could cause a major loss of carbon due to high respiration rates (Lange et al., 2000). In the course of our study, the lowest temperatures predominantly occurred during the night, contributing to lower respiration rates, and values were mostly below the upper TCP. Thus, the temperature did not seem to be a limiting factor for the physiological activity of epiphytic bryophytes in this environment (Fig. S10). Similarly, Wagner and coauthors (Wagner et al., 2013) stated that the temperature likely was not a limiting factor for the overall carbon balance of the bryophytes investigated in a low- and highland rainforest in Panama. ~~Unexpectedly, the WC of bryophytes has been shown to be higher in the canopy than in the understory. In the understory, the WCP was surpassed in 4-54 % of the time during the dry season and in 53-95 % of the time during the wet season, whereas at 18 and 23 m it was exceeded in 93 – 100 % of the time, without a clear difference between the seasons. In the understory, the WC of cryptogams seemed to be predominantly regulated by rain events, whereas in the canopy, the samples stayed relatively homogeneously wet over long~~

~~time spans (Fig. 2). This was unexpected at first sight, as one would expect them to dry quickly at the higher canopy levels. However, as the samples at the two upper canopy levels grew “sitting on top” of nearly horizontal branches, they presumably could store the water over longer time spans as compared to the bryophytes at the lower trunk section, which grew on the vertical stem. Additionally, the liverwort community in the canopy seemed to form thicker and denser cushions, which could store water more effectively as compared to the mosses in the understory, which occurred in thin and rather loose cushions (Fig. S4).~~

~~It is difficult to distinguish between the effect of fog and high RH, as fog occurs when high RH values persist already. However, some events indicate that the WC of bryophytes could increase upon fog (Fig. S9S6), which has also been shown in some other studies (León-Vargas et al., 2006). Also condensation needs to be considered as a water source for cryptogams, as demonstrated for epiphytic lichens (Lakatos et al., 2012). In their study on corticolous epiphytic lichens in a tropical lowland cloud forest, Lakatos and coauthors showed that lichens benefit from dew formation on the thallus surface during noon, and we can assume similar processes to occur quite regularly on epiphytic cryptogams (Lakatos et al., 2012). Unfortunately, this factor could not be evaluated in this study, because some relevant parameters for its calculation were not monitored.~~

~~Considering a tropical forest environment, the air humidity and temperature have to be considered from the understory to the canopy, as limiting factors for survival and growth (Kumagai et al., 2001; Campos et al., 2019). The microhabitats in height zones along a tree (from the base to the outer canopy) are influenced by the leaf area index where branches and trunk converge (Caldararu et al., 2012; Xiao et al., 2014). The differentiation between the height zones changes the microclimate conditions of the bryophytes along the tree (Campbell and Coxson, 2001; de Oliveira et al., 2009).~~

Utilizing the compensation points of water, light, and temperature taken from the literature, one can make rough estimates of the ~~physiological activity patterns of the bryophytes~~ time fractions when NP and DR occur at the different height levels (Table 3). ~~Whereas the lower end of the WCP range (30 % DW) was exceeded during 100 % of the time by the liverworts at the two uppermost height levels, the liverworts at 8 m exceeded this value only in 86 % of the time during the dry season and in 98 % of the time during the wet season. The mosses at 1.5 m height exceeded this value in 54 % of the time during the dry season and in 95 % of the time during the wet season. Considering a WCP of 80 %, the mosses in the understory only exceed this value in 4 % and in 53 % of the time during the dry and the wet season, respectively. Thus, for mosses in the understory, the level of the WCP is highly relevant, whereas for the liverworts in the canopy the complete range of values allows long durations of physiological activity. For the LCP_l (ranging between 3 and 12 μmol m^{-2} s^{-1}) an even more critical pattern was observed, as the communities at the ground level surpassed it only in 4-16 % and in 2-19 % of the time during the dry and the wet season, respectively. In contrast to this, bryophytes at the higher levels (18, 23 m) surpassed these CPs in 38-47 % and in 34-46 % of the time during the dry and the wet season, respectively. Contrastingly, the temperature only rarely was limiting NP and there were no major differences between the height levels or the seasons. At all~~

~~height levels T_{opt} was reached in 56-60 35 % of the time during the dry season and in 24-77 54 % of the time during the wet season.~~

~~Combining the ranges of compensation points allows, a rough estimation of the time fractions when NP and DR occur. Our~~ These data suggest that at the upper ~~two~~ height level~~s~~ NP occurred in ~~27-43~~1-30 % and DR in ~~56-66~~2-52 % of the time during the wet season and in ~~21-43~~1-24 % (NP) and in ~~51-59~~4-45 % (DR) of the time during the dry season, respectively (Table 3). These estimates suggest that the duration of DR was about twice as long as that of NP. For the samples at 8 m height the results were similar, whereas for those in the understory the duration of DR was about 5- to 30-fold higher than the duration of NP. ~~At the understory, however, the durations of physiological activity waswere relatively short and the results for the lowest level suggested that NP and DR occurred in only in 1-15 13 % (NP) and in 53-7932-67 % (DR) of the time during the wet season and in 0-10 5 % (NP) and in 16-5210-26 % (DR) of the time during the dry season.~~ The large discrepancy between the time ranges for NP and DR calculated for the bryophytes in the ~~canopy and the~~ understory gives reason to expect the LCP$_l$ and the WCP to be at the lower end of the range (3 µmol m^{-2} s^{-1}, 30 %) for the bryophytes at the lowest height level and to be at the upper end of the range (12 µmol m^{-2} s^{-1}, 80 %) for the bryophytes at the two upper~~most~~ height levels. For other habitats, LCP$_l$~~s~~ values as low as 1 µmol m^{-2} s^{-1} have been defined for lichens (Green et al., 1991), and thus it could be possible that the bryophyte communities in the understory exhibit similarly low LCP$_l$ values.

~~However, one also has to keep in mind that the uncertainty inherent in the microclimatic data directly impacts the calculated physiological patterns.height level conditions such as , and wind velocity (Barkman, 1958; Cornelissen and Ter Steege, 1989; Oliveira and Oliveira, 2016; Sierra et al., 2018; Campos et al., 2019).~~

In the environment being studied, the acclimation of the organisms to the environmental conditions is also crucial for their survival. Thus, the time ranges of metabolic activity are only rough estimates, depending on the actual compensation points, which are influenced by inter- and intraspecific variation. There are also some differences between groups, as, e.g., lichens tend to perform photosynthesis at lower WCs than bryophytes, and chlorolichens (with green algae as photobionts) may utilize high air humidity, whereas cyanolichens (cyanobacteria as photobiont) need liquid water (Green et al., 2011; Lange and Kilian, 1985; Raggio et al., 2017). Furthermore, there are also differences between the bryophyte divisions of mosses and liverworts, and also within one division the interspecific variability can also be large.

5 Conclusions

The microclimatic conditions experienced by bryophytes are being assessed in long-term measurements at the ATTO site since October 2014. These measurements provide a unique data set of the micrometeorological conditions within the understory and the inner canopy of tropical rain forests and facilitate a rough estimation of the physiological activity patterns of epiphytic bryophytes along a vertical gradient. Within this tropical rain forest habitat, the WC has turned out to be the key parameter controlling the overall physiological activity of the organisms with major differences between organisms of the canopy and the understory. In the understory, the WC of the bryophytes responded reliably upon rain events, and after major rain events, the samples could stay wet for several days before they dried out again~~was mostly relatively low and only stayed high for a few days after an intense rain event~~. In contrast to that, the WC of the bryophytes in the canopy responded only very rarely to rain events during the wet season, probably caused by the dense foliage, and kept relatively stable low water contents. During the dry season, probably due to the less dense foliage, they responded to some rain events and showed a regular nightly increase in water contents, which might be a combined effect of nightly condensation and thallus morphology (life form). ~~at higher levels remains high over most of the time, probably caused by the bryophyte morphology and also their growth habitat on top of inclined or horizontal branches. In the canopy, the dominating liverworts responded to the nightly increase of the RH, which was not observed for the mosses in the understory.~~ Thus, our data suggest that the relevant water source for bryophytes in the understory might be rain, while for the bryophytes in the canopy ~~the nightly increase of the RH~~nightly condensation might be relevant for an activation of the physiological processes. The light intensity during periods of physiological activity mainly determines whether NP dominates or carbon is lost by dominating respiration. As the temperature shows only minor spatial, diel, and seasonal variation relative to the physiological tolerance of the bryophytes, it seems to be of minor physiological relevance within the given habitat.

Data on the potential physiological activity of bryophytes and cryptogamic organisms in general are not only relevant for their potential role in carbon cycling, but may also provide new insights into their relevance as sources of bioaerosols and different trace gases. Thus, these data may form a baseline for studies investigating the overall relevance of cryptogams in the context of biogeochemical cycling in tropical habitats. However, the wide ranges of potential activity and the scarcity of literature data illustrate the necessity of CO_2 gas exchange measurements to assess the actual diel and seasonal physiological activity and productivity of rain forest cryptogams under varying environmental conditions.

Data availability

All data are deposited in a data portal, which is accessible via the homepage of the ATTO project (https://www.attoproject.org/) upon request.

Supplement link

Author contribution

BW, CP, and NL designed the measurement setup. NL, CGGB, SB, RPA and APPF conducted the practical measurements. NL, DW, GRC, MS, AA, LRO, FD, and SMO compiled the data and conducted the analyses. All authors discussed the results. NL and BW prepared the manuscript with contributions from all co-authors.

Disclaimer

The authors declare that they have no conflict of interest.

Special issue statement

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Tables

Table 1: Annual mean values and standard deviations (± SD) of mean daytime photosynthetically active radiation (PAR$_{avg}$), ~~daily maxima of photosynthetically active radiation (PAR$_{max}$),~~ temperature, and water contents (WC) of bryophytes at the three~~four~~ height levels and above the canopy (a). Annual sum of rain and fog days as well as the annual sum of rain (b). Mean values were calculated from 30~~5~~-minute intervals~~, whereas for PAR$_{max}$ the daily maximum values were considered~~. Due to data gaps in the measured rain (shown in brackets), missing values were also extrapolated from existing data as described in methods section (values behind the brackets). Values for PAR$_{max}$ can be found in Table S6.

(a)

Height	**2015**		**2016**	
	Mean	**SD**	**Mean**	**SD**
PAR$_{avg}$ daytime[µmol m^{-2} s^{-1}]				
above-canopy	819	596	824	599
23 m	32	37	49	52
8 m	43	50	8	14
1.5 m	5	15	3	8
Temperature [°C]				
above-canopy	26.6	3.4	26.4	3.1
23 m	26.1	3.0	26.8	3.3
8 m	25.8	2.3	25.8	1.9
1.5 m	25.4	1.8	25.5	1.5
Water content [%]; above canopy RH [%]				
above-canopy	86	15	90	13
23 m	39	30	47	69
8 m	70	45	73	72
1.5 m	64	85	38	53

~~**Height [m]**~~	~~**2015**~~		~~**2016**~~	
	~~**Mean**~~	~~**± SD**~~	~~**Mean**~~	~~**± SD**~~
~~**PAR$_{avg}$ daytime[µmol m^{-2} s^{-1}]**~~			-	-
~~above canopy, 75~~	~~911~~	~~678~~	~~841~~	~~653~~
~~23~~	~~34~~	~~1~~	~~58~~	~~8~~
~~18~~	~~45~~	~~15~~	~~34~~	~~11~~
~~8~~	~~35~~	~~19~~	~~17~~	~~10~~
~~1.5~~	~~5~~	~~35~~	4	~~20~~
~~**PAR$_{max}$ [µmol m^{-2} s^{-1}]**~~			-	
~~above canopy, 75~~	~~2043~~	~~579~~	~~2153~~	~~433~~
~~23~~	~~320~~	~~24~~	~~497~~	~~51~~
~~18~~	~~310~~	~~38~~	~~331~~	~~26~~
~~8~~	~~322~~	~~236~~	~~116~~	~~86~~
~~1.5~~	~~172~~	~~0~~	~~99~~	~~140~~

~~Temperature [°C]~~		-	-	-
~~above canopy, 26~~	~~26.6~~	~~3.4~~	~~26.4~~	~~3.1~~
~~23~~	~~25.9~~	~~1.0~~	~~26.5~~	~~0.5~~
~~18~~	~~26.2~~	~~0.0~~	~~26.3~~	~~0.0~~
~~8~~	~~25.8~~	~~0.2~~	~~25.8~~	~~0.2~~
~~1.5~~	~~25.4~~	~~0.0~~	~~25.5~~	~~0.1~~
~~Water content [%]~~			-	-
~~23, Liverwort~~	~~282~~	~~117~~	~~280~~	~~438~~
~~18, Liverwort~~	~~181~~	~~50~~	~~308~~	~~309~~
~~8, Liverwort~~	~~52~~	~~14~~	~~140~~	~~288~~
~~8, Moss~~	~~182~~	~~93~~	~~167~~	~~256~~
~~1.5 Moss~~	~~86~~	~~37~~	~~69~~	~~415~~

(b)

Parameter	**2015**	**2016**
	Sum	**Sum**
Rain (days)	(199) 202	(197) 215
(mm)	(1680) 1693	(1702) 1863
Fog (days)	21*	28*

*: Gaps in the data record due to malfunction of fog sensor during time window of 31.05. – 20.10.2015, 30.04. – 06.07.2016, and 01.09. – 31.12.2016.

Table 2 Seasonal mean values and standard deviations (± SD) of the mean photosynthetically active radiation (PAR$_{avg}$), ~~the daily maximum of photosynthetically active radiation (PAR$_{max}$),~~ the temperature, and the above-canopy relative humidity (RH) or water content (WC) of bryophytes determined at different height levels and above the canopy. Mean values for the respective seasons were calculated from 30~~5~~-minute intervals ~~of the years 2015 and~~from October 2014 to November 2016~~, except for PARmax, where the daily maximum values were considered.~~ Values for PAR$_{max}$ can be found in Table S7.

Height	**PAR$_{avg}$ daytime [µmol m^{-2} s^{-1}]**		**Temperature [°C]**		**RH (above-canopy) [%], WC [%]**	
[m]	Mean	± SD	Mean	± SD	Mean	± SD
Wet season						
above-canopy	738	46	25.7	0.7	94	2
23 m	27	17	25.3	0.6	41	3
8m	41	24	24.9	0.4	93	21
1.5	3	1	24.9	0.4	83	26
Transitional season Wet-Dry						
above-canopy	860	53	25.6	0.5	91	2
23 m	38	29	25.7	0.7	49	4
8 m	63	14	24.9	0.4	72	27
1.5 m	2	1	24.6	0.2	31	6
Dry season						
above-canopy	950	93	27.2	1.0	84	6
23 m	54	21	27.8	1.2	45	10
8 m	24	17	26.6	0.9	58	20
1.5 m	5	4	26.0	0.8	30	31
Transitional season Dry-Wet						
above-canopy	784	111	26.5	1.6	87	8
23 m	52	34	27.1	2.2	37	2
8 m	23	5	26.2	1.7	58	13
1.5 m	4	1	25.9	1.4	52	53

~~**Height**~~	~~**PAR$_{avg}$ daytime [µmol m^{-2} s^{-1}]**~~		~~**PAR$_{max}$ [µmol m^{-2} s^{-1}]**~~		~~**Temperature [°C]**~~		~~**RH (above-canopy) [%], WC [%]**~~	
~~[m]~~	~~Mean~~	~~± SD~~	~~Mean~~	~~± SD~~	~~Mean~~	~~±~~	~~Mean~~	~~± SD~~
~~**Wet season**~~								
~~above-canopy~~	~~738~~	~~566~~	~~2086~~	~~515~~	~~25.6~~	~~2.5~~	~~95~~	~~9~~
~~23 Liverwort~~	~~30~~	~~3~~	~~248~~	~~194~~	~~25.3~~	~~2.0~~	~~283~~	~~83~~
~~18 Liverwort~~	~~39~~	~~12~~	~~282~~	~~175~~	~~25.2~~	~~1.9~~	~~197~~	~~66~~
~~8 Liverwort~~	~~31~~	~~26~~	~~144~~		~~24.9~~	~~1.1~~	~~66~~	~~22~~
~~8 Moss~~							~~182~~	~~63~~
~~1.5 Moss~~	4	~~15~~	~~114~~	~~224~~	~~24.9~~	~~1.0~~	~~121~~	~~91~~

~~Transitional season Wet-Dry~~								
~~above canopy~~	~~861~~	~~649~~	~~2227~~	~~182~~	~~25.8~~	~~3.0~~	~~91~~	~~11~~
~~23 Liverwort~~	~~41~~	~~72~~	~~414~~	~~252~~	~~25.7~~	~~2.8~~	~~308~~	~~109~~
~~18 Liverwort~~	~~44~~	~~54~~	~~351~~	~~123~~	~~25.4~~	~~2.3~~	~~200~~	~~34~~
~~8 Liverwort~~	~~66~~	~~88~~	~~165~~	~~218~~	~~24.9~~	~~1.4~~	~~53~~	~~10~~
~~8 Moss~~							~~161~~	~~56~~
~~1.5 Moss~~	~~2~~	~~12~~	~~61~~	~~102~~	~~24.6~~	~~1.1~~	~~55~~	~~28~~
~~Dry season~~								
~~above canopy~~	~~973~~	~~647~~	~~2100~~	~~609~~	~~26.7~~	~~3.4~~	~~87~~	~~14~~
~~23 Liverwort~~	~~55~~	~~9~~	~~503~~	~~231~~	~~27.2~~	~~3.5~~	~~273~~	~~125~~
~~18 Liverwort~~	~~41~~	~~13~~	~~412~~	~~190~~	~~26.5~~	~~2.9~~	~~188~~	~~89~~
~~8 Liverwort~~	~~23~~	~~16~~	~~295~~	~~268~~	~~26.0~~	~~2.1~~	~~63~~	~~45~~
~~8 Moss~~							~~166~~	~~70~~
~~1.5 Moss~~	~~6~~	~~25~~	~~209~~	~~299~~	~~25.5~~	~~1.7~~	~~53~~	~~37~~
~~Transitional season Dry-Wet~~								
~~above canopy~~	~~785~~	~~617~~	~~1988~~	~~509~~	~~26.5~~	~~3.3~~	~~85~~	~~15~~
~~23 Liverwort~~	~~55~~	~~91~~	~~530~~	~~297~~	~~27.2~~	~~3.7~~	~~289~~	~~113~~
~~18 Liverwort~~	~~37~~	~~28~~	~~185~~	~~109~~	~~26.6~~	~~3.0~~	~~227~~	~~121~~
~~8 Liverwort~~	~~21~~	~~47~~	~~269~~	~~178~~	~~26.3~~	~~2.5~~	~~112~~	~~84~~
~~8 Moss~~							~~180~~	~~67~~
~~1.5 Moss~~	4	~~20~~	~~107~~	~~113~~	~~26.0~~	~~2.1~~	~~74~~	~~60~~

Table 3: The potential time fractions [%], during which the epiphytic bryophytes at the different height levels exceeded the lower compensation points of light (LCP_l), the upper compensation points for temperature (TCP), the lower compensation points for water (WCP), and reached the optimal temperature for net photosynthesis (T_{opt}). The results are shown separately for a) the wet season (February–May) and b) the dry season (August–November). Values are given for the different height levels (1.5, 8, ~~18,~~ 23 m) and bryophyte divisions (M=moss, L=liverwort). For the net photosynthesis (NP) it is required that WC > WCP, PAR > LCP_l and T > TCP, for the dark respiration (DR) it is necessary that WC > WCP and PAR < LCP_l or WC > WCP and T > TCP. ~~Five~~Thirty~~30~~-minute averages of measurements during the entire measurement period from October 2014 to November~~December~~ 2016 were considered. The ranges of the compensation points (CP) and the optimum temperature (opt) were reported in Lösch (1994) and Wagner et al. (2013) (see Table S4).

a) Wet season

Height	**Division**	**LCP_l**	**T_{opt}**	**TCP**	**WCP**	**NP**	**DR**
		≥ 3-12	24.0-27.0	≥ 30.0-36.0	≥ 30-80		
		µmol m^{-2} s^{-1}	° C	° C	% DW		
[m]	**L/M**	**Time fraction when cardinal points are reached/exceeded [% of time]**					
23	L	33-43	4-54	0-3	3-80	1-30	2-52
8	M & L	24-31	2-74	0	42-94	14-35	29-59
1.5	M	2-19	2-77	0	32-80	1-13	32-67

b) Dry season

Height	**Division**	**LCP_l**	**T_{opt}**	**TCP**	**WCP**	**NP**	**DR**
		≥ 3-12	24.0-27.0	≥ 30.0-36.0	≥ 30-80		
		µmol m^{-2} s^{-1}	° C	° C	% DW		
[m]	**L/M**	**Time fraction when cardinal points are reached/exceeded [% of time]**					
23	L	40-46	6-35	0-27	6-64	1-24	4-45
8	M & L	18-35	8-51	0-11	5-84	2-34	7-51
1.5	M	3-16	9-59	0-4	2-21	0-5	10-26

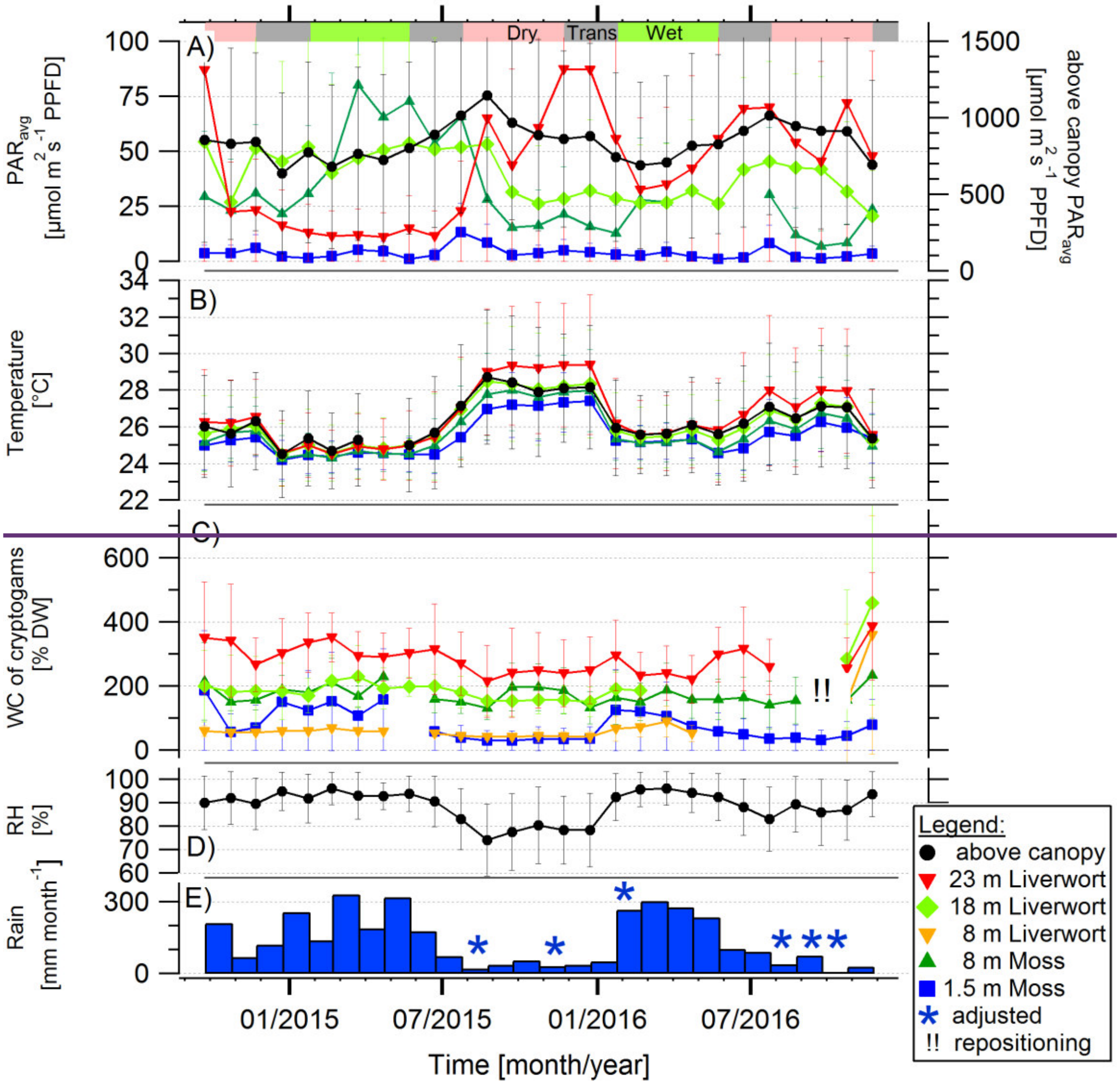
~~a) Wet season~~

~~**Height**~~	~~**Division**~~	~~**LCP_l**~~	~~**T_{opt}**~~	~~**TCP**~~	~~**WCP**~~	~~**NP**~~	~~**DR**~~
		~~≥ 3-12~~	~~24.0-27.0~~	~~≥ 30.0-36.0~~	~~≥ 30-80~~		
		~~µmol m^{-2} s^{-1}~~	~~° C~~	~~° C~~	~~% DW~~		
~~**[m]**~~	~~**L/M**~~	~~**Time fraction when cardinal points are reached/exceeded [% of time]**~~					
~~23~~	~~L~~	~~34-43~~	~~4-54~~	~~0-3~~	~~98-100~~	~~27-38~~	~~62-66~~
~~18~~	~~L~~	~~40-46~~	~~4-55~~	~~0-2~~	~~96-100~~	~~32-43~~	~~56-57~~
~~8~~	~~L~~	~~25-31~~	~~2-74~~	~~0~~	~~18-98~~	~~5-40~~	~~11-56~~
~~8~~	~~M~~				~~88-100~~	~~26-36~~	~~54-63~~
~~1.5~~	~~M~~	~~2-19~~	~~2-77~~	~~0~~	~~53-95~~	~~1-15~~	~~53-79~~

~~b) Dry season~~

~~Height~~	~~Division~~	~~LCP$_l$~~	~~T$_{opt}$~~	~~TCP~~	~~WCP~~	~~NP~~	~~DR~~
		~~≥ 3-12~~	~~24.0-27.0~~	~~≥ 30.0-36.0~~	~~≥ 30-80~~		
		~~µmol m^{-2} s^{-1}~~	~~° C~~	~~° C~~	~~% DW~~		
~~[m]~~	~~L/M~~	~~Time fraction when cardinal points are reached/exceeded [% of time]~~					
~~23~~	~~L~~	~~42-47~~	~~6-34~~	~~3-26~~	~~96-100~~	~~18-41~~	~~57-59~~
~~18~~	~~L~~	~~38-46~~	~~5-40~~	~~0-23~~	~~93-100~~	~~21-43~~	~~51-54~~
~~8~~	~~L~~	~~19-36~~	~~8-52~~	~~0-10~~	~~5-86~~	~~3-34~~	~~15-55~~
~~8~~	~~M~~				~~84-98~~	~~14-39~~	~~52-56~~
~~1.5~~	~~M~~	~~4-16~~	~~9-60~~	~~0-3~~	~~4-54~~	~~0-10~~	~~16-52~~

Figures


Dry
Trans
Wet
A)
B)
C)
D)
E)
PAR$_{avg}$ [µmol m^{2} s^{-1} PPFD]
above canopy PAR$_{avg}$ [µmol m^{2} s^{-1} PPFD]
100
75
50
25
0
1500
1000
500
0
Temperature [°C]
34
32
30
28
26
24
22
WC of cryptogams [% DW]
600
400
200
0
!!
RH [%]
100
90
80
70
60
Rain [mm month^{-1}]
300
0
*
01/2015
07/2015
01/2016
07/2016
Time [month/year]
Legend:
● above canopy
▼ 23 m Liverwort
◆ 18 m Liverwort
▼ 8 m Liverwort
▲ 8 m Moss
■ 1.5 m Moss
* adjusted
!! repositioning

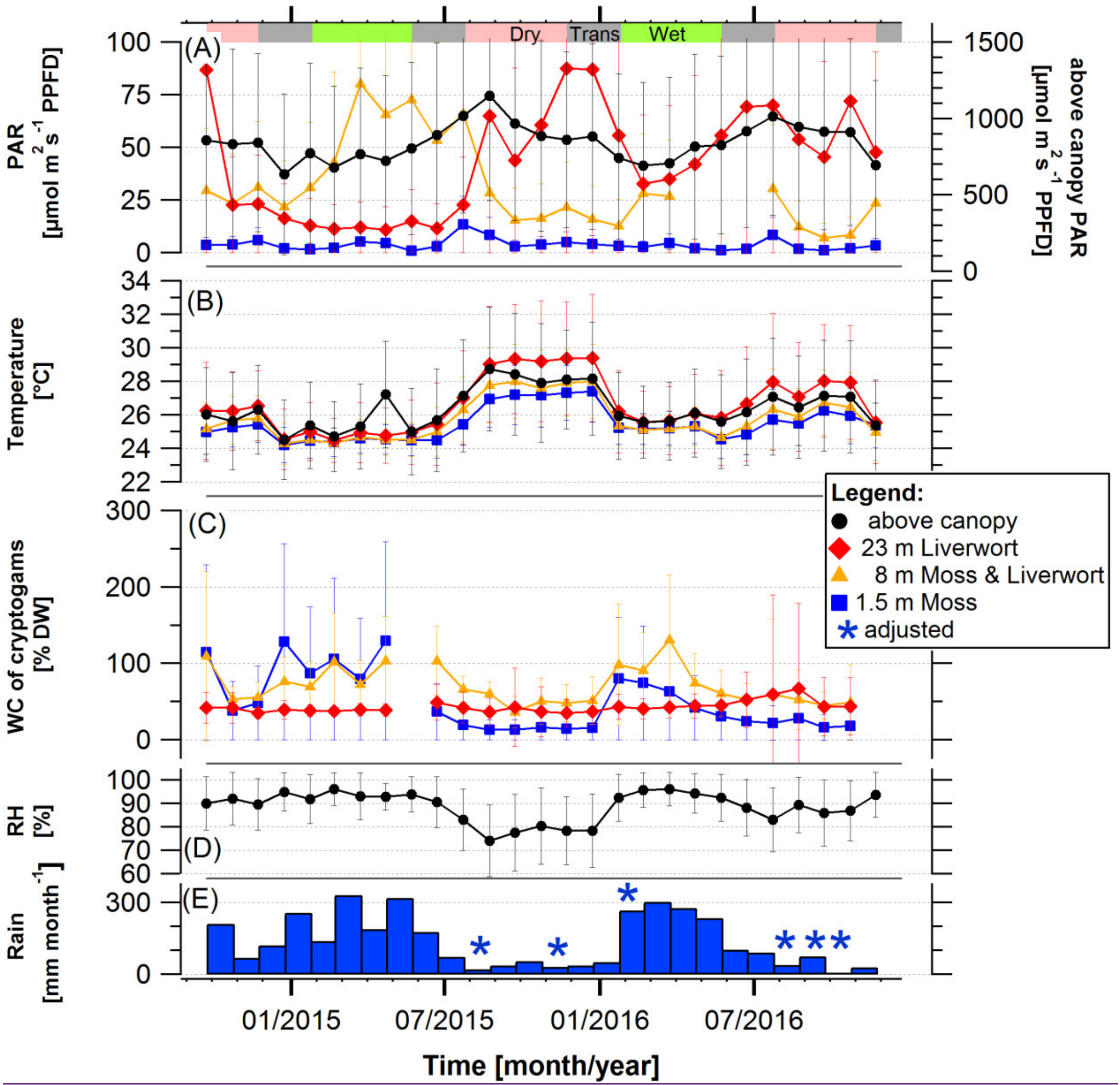
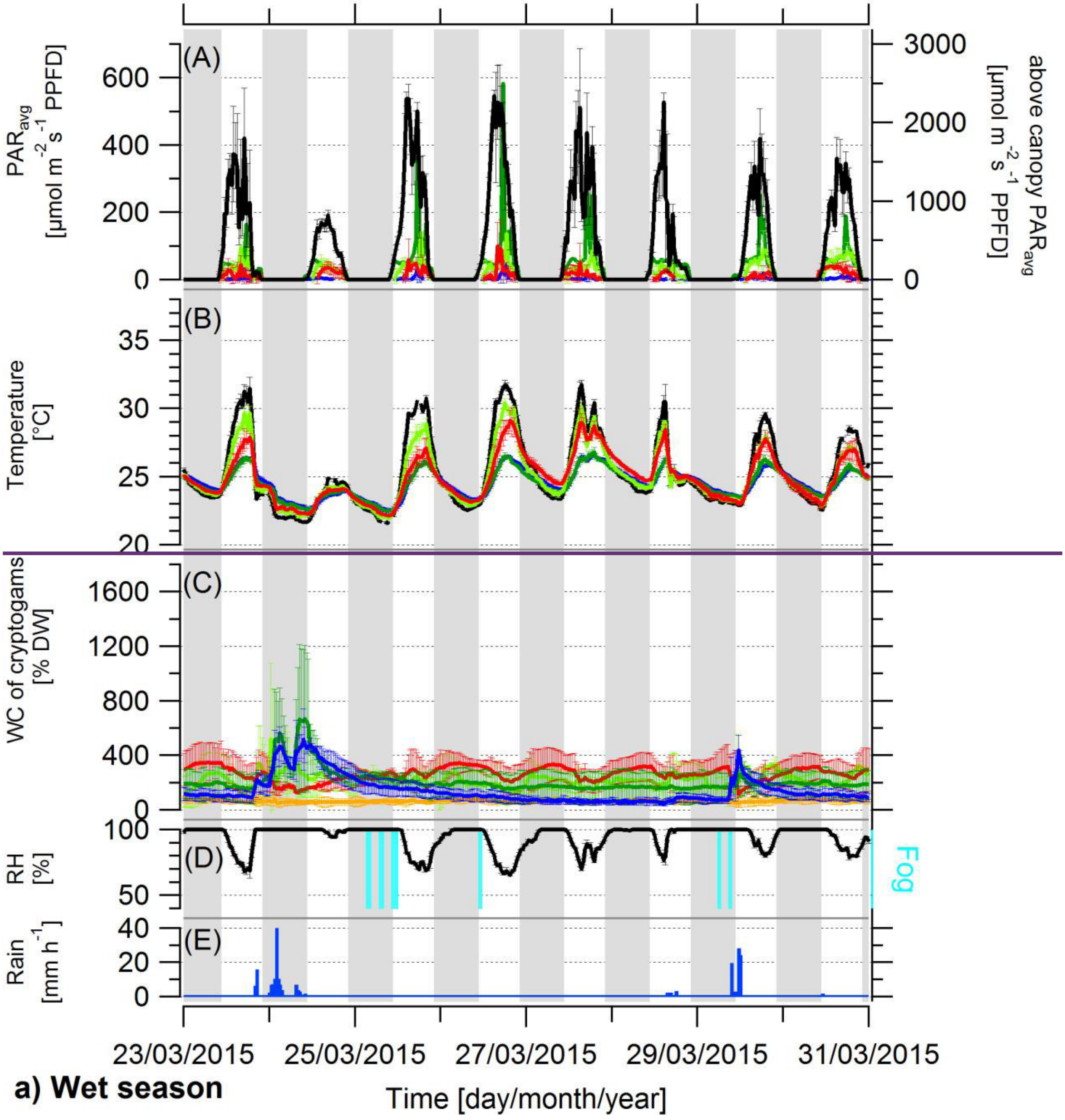
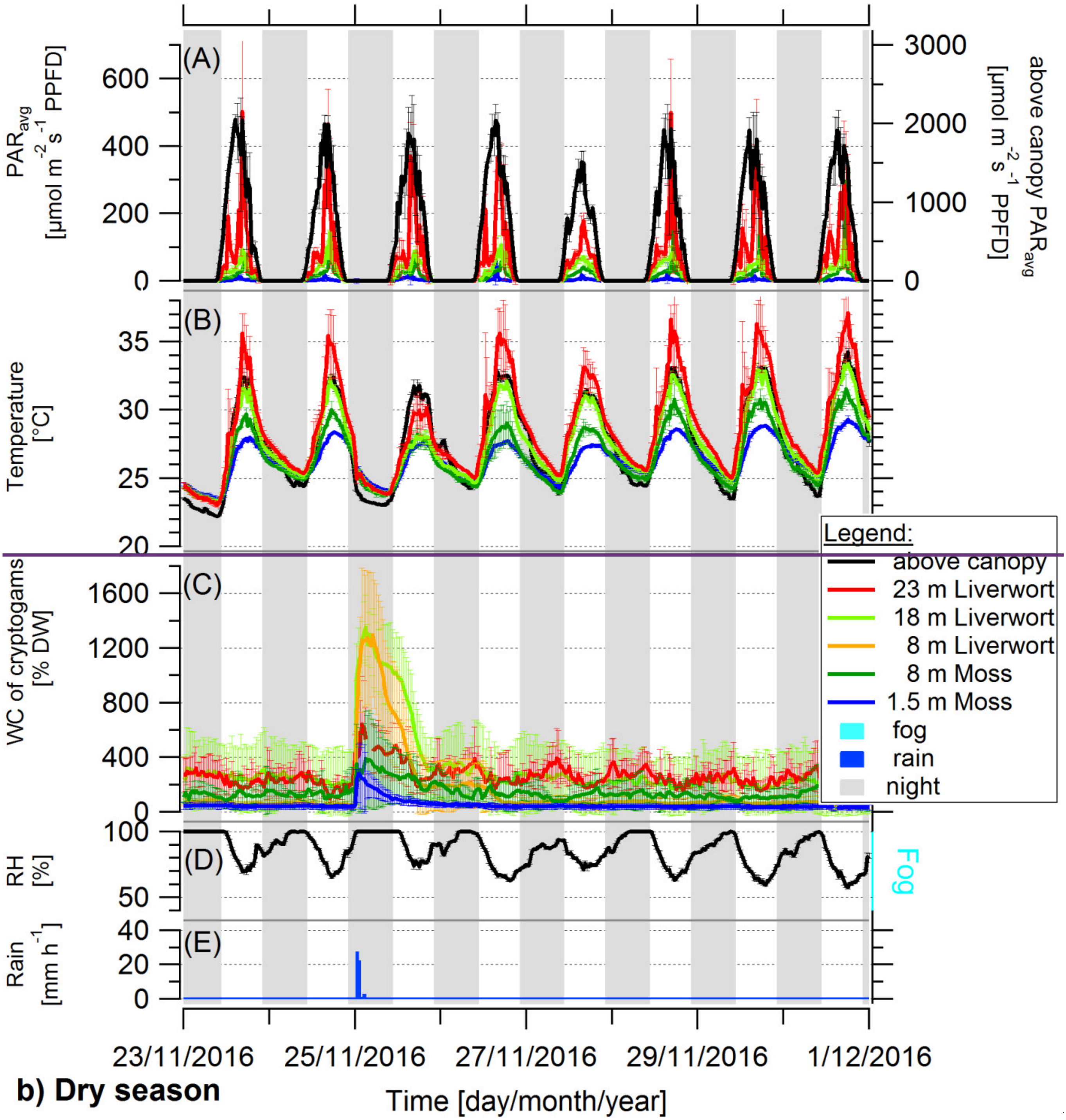


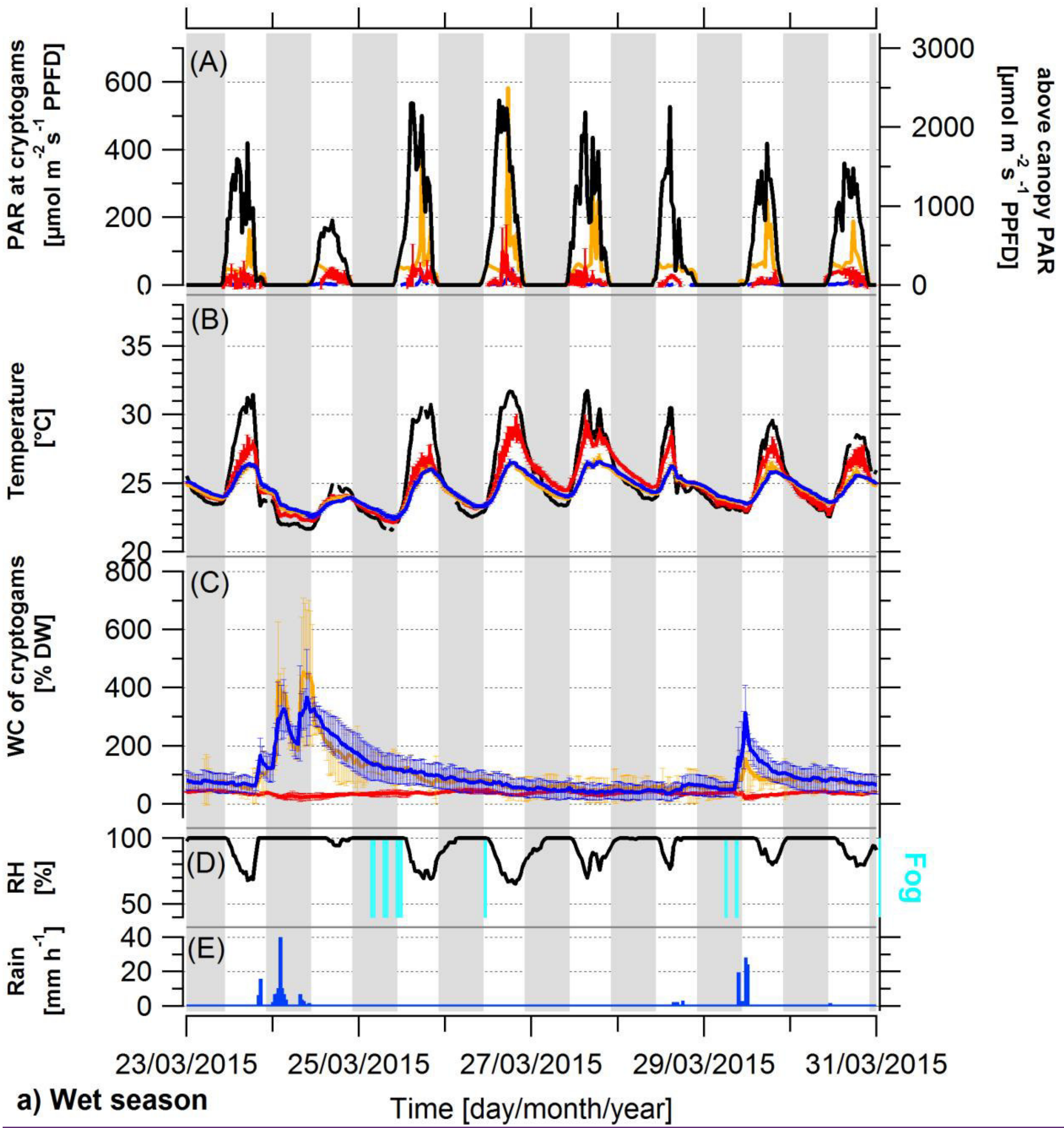
Figure 1: Mean light condition (PAR~~avg~~), temperatures, and water content (WC) experienced by bryophyte communities, and above-canopy meteorological conditions in the Amazonian rain forest. The micrometeorological parameters on top/within epiphytic cryptogamic communities represent monthly mean values ± SD of (A) daily average (06:00 – 18:00 LT) of photosynthetically active radiation (PAR~~avg~~) on top, (B) temperature within, and (C) WC of cryptogamic communities. The above-canopy meteorological parameters comprise the (A) monthly mean value of the daily average (06:00 – 18:00 LT) of above-canopy photosynthetically active radiation (PAR~~avg~~ at 75 m), (B) monthly mean value of above-canopy temperature (at 26 m), (D) monthly mean value of relative air

humidity (RH at 26 m height), and (E) monthly amount of rain. Data of replicate sensors installed within communities at the same height level were pooled, while above-canopy parameters were measured with one sensor each. Colored horizontal bars in the upper part of the figure indicate the seasons. Exact values and additional data are presented in Tables ~~S4~~ S3 and ~~S6~~S5.


(A)
PARavg [µmol m-2 s-1 PPFD]
0
200
400
600
above canopy PARavg [µmol m-2 s-1 PPFD]
0
1000
2000
3000
(B)
Temperature [°C]
20
25
30
35
(C)
WC of cryptogams [% DW]
0
400
800
1200
1600
(D)
RH [%]
50
100
Fog
(E)
Rain [mm h-1]
0
20
40
23/03/2015
25/03/2015
27/03/2015
29/03/2015
31/03/2015
Time [day/month/year]
a) Wet season


(A)
PAR$_{avg}$ [µmol m^{-2} s^{-1} PPFD]
0
200
400
600
above canopy PAR$_{avg}$ [µmol m^{-2} s^{-1} PPFD]
0
1000
2000
3000
(B)
Temperature [°C]
20
25
30
35
(C)
WC of cryptogams [% DW]
0
400
800
1200
1600
Legend:
above canopy
23 m Liverwort
18 m Liverwort
8 m Liverwort
8 m Moss
1.5 m Moss
fog
rain
night
(D)
RH [%]
50
100
Fog
(E)
Rain [mm h^{-1}]
0
20
40
23/11/2016
25/11/2016
27/11/2016
29/11/2016
1/12/2016
Time [day/month/year]

b) Dry season


(A)
PAR at cryptogams [µmol m^{-2} s^{-1} PPFD]
0
200
400
600
above canopy PAR [µmol m^{-2} s^{-1} PPFD]
0
1000
2000
3000
(B)
Temperature [°C]
20
25
30
35
(C)
WC of cryptogams [% DW]
0
200
400
600
800
(D)
RH [%]
50
100
Fog
(E)
Rain [mm h^{-1}]
0
20
40
23/03/2015
25/03/2015
27/03/2015
29/03/2015
31/03/2015
Time [day/month/year]

a) Wet season

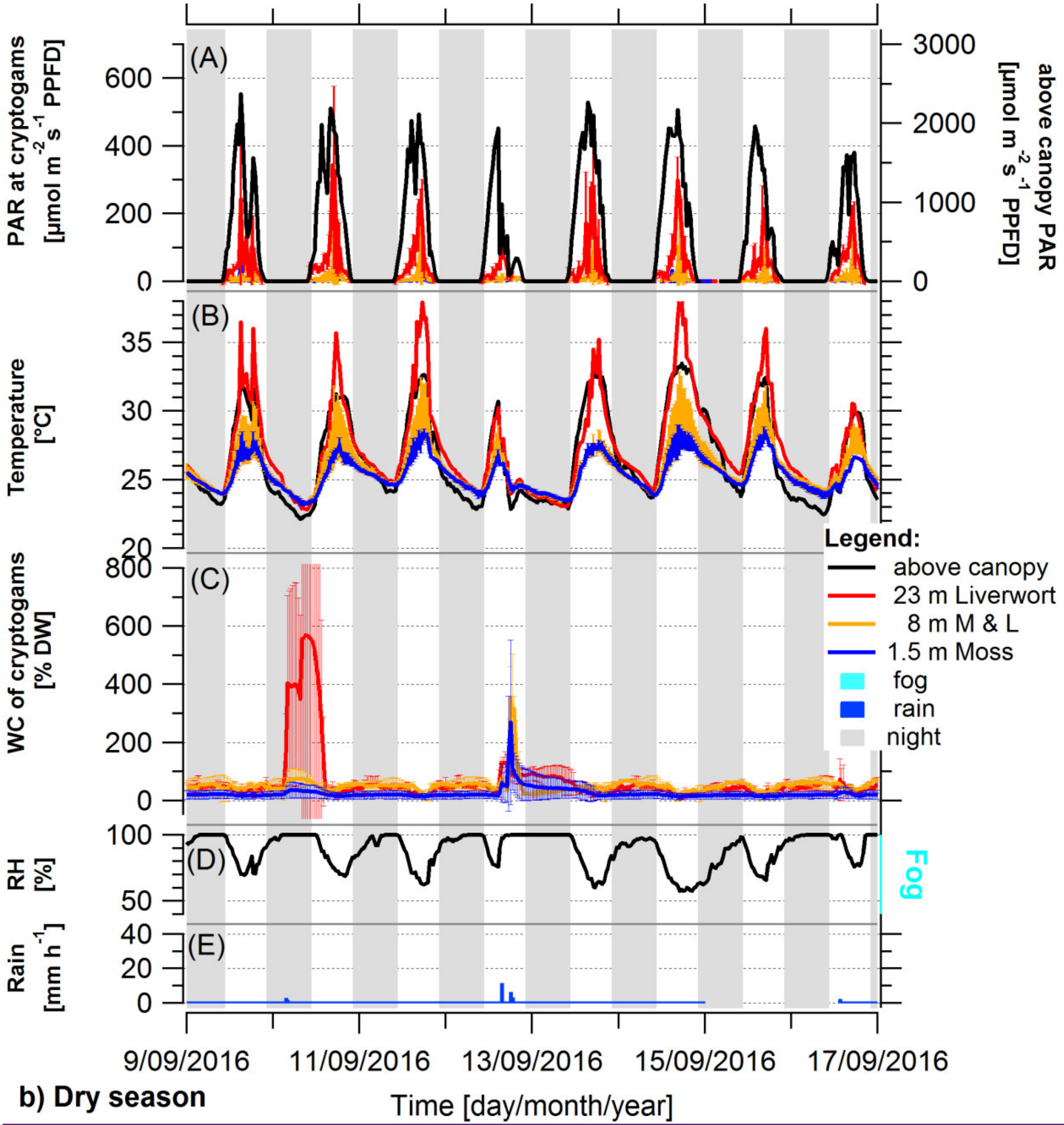
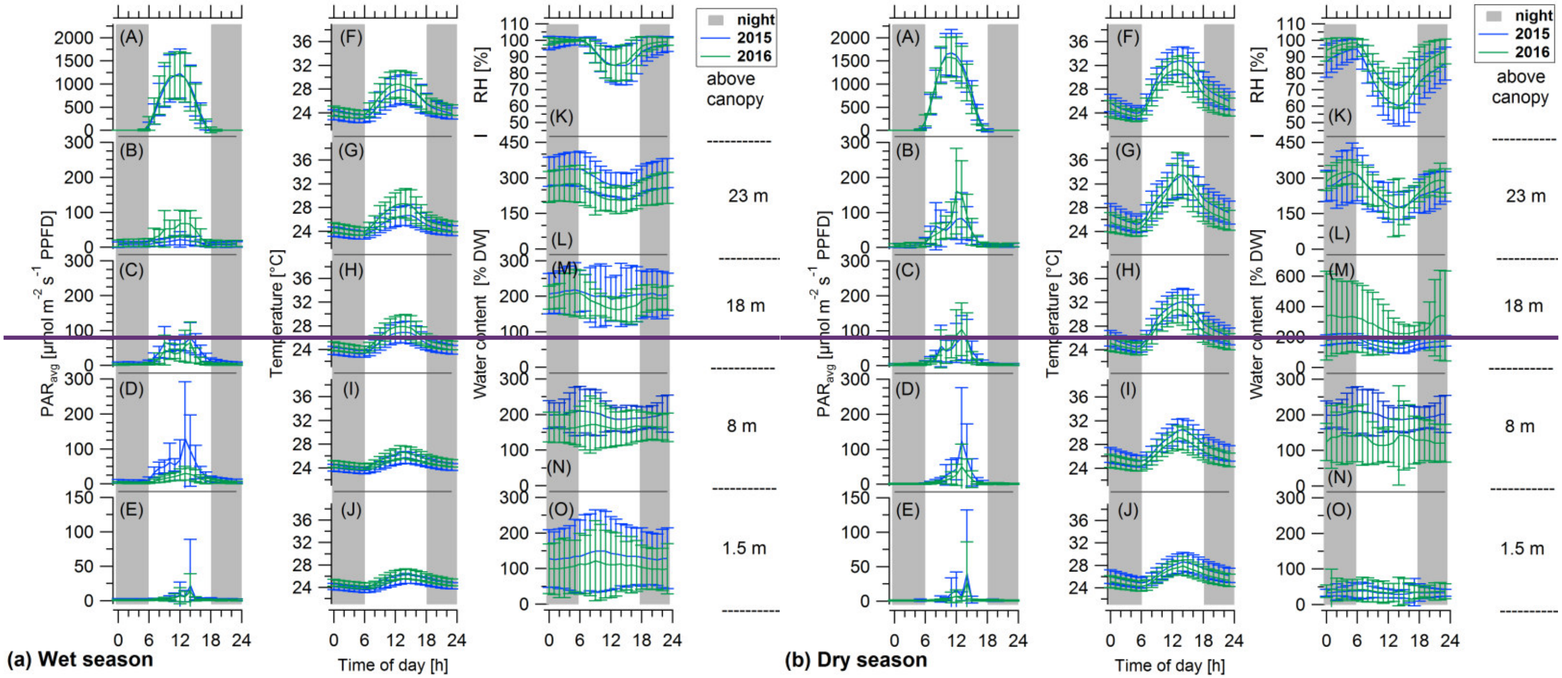


Figure 2: Representative periods during the wet and dry season under average conditions, showing light condition (PAR~~$_{avg}$~~), temperature, and water content (WC) of bryophytes, and above-canopy meteorological conditions in the Amazonian rain forest. Shown are 8-day periods during (a) the wet season 2015 and (b) the dry season 2016. The micrometeorological parameters on top/within epiphytic cryptogamic communities represent (A) the photosyn-

thetically active radiation (PAR~~$_{avg}$~~) on top, (B) the temperature within, and (C) the WC of cryptogamic communities. The above-canopy meteorological parameters comprise (A) above-canopy photosynthetically active radiation (PAR~~$_{avg}$~~ at 75 m), (B) above-canopy temperature (at 26 m), (D) relative air humidity (RH at 26 m height), presence of fog events, and (E) rain amount. The data show 30-minute averages ± SD except for rain, which shows hourly sums. Data of replicate sensors installed within communities at the same height level were pooled, while above-canopy parameters were measured with one sensor each. The nighttime is shaded in grey (06:00 – 18:00 LT).


(a) Wet season
(b) Dry season
night
2015
2016
above canopy
23 m
18 m
8 m
1.5 m
(A)
(B)
(C)
(D)
(E)
(F)
(G)
(H)
(I)
(J)
(K)
(L)
(M)
(N)
(O)
PAR$_{avg}$ [µmol m^{-2} s^{-1} PPFD]
Temperature [°C]
RH [%]
Water content [% DW]
Time of day [h]
0
6
12
18
24
0
500
1000
1500
2000
100
200
300
50
150
24
28
32
36
60
70
80
90
110
450
600

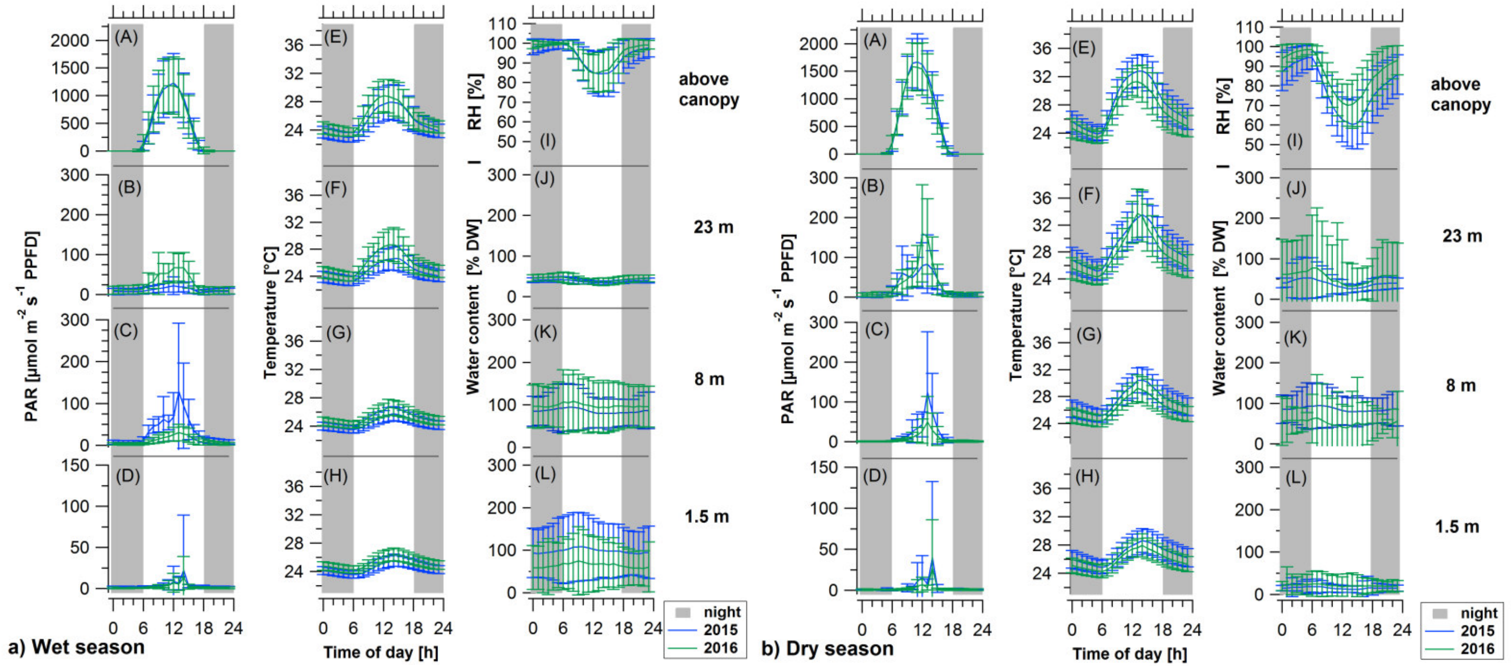
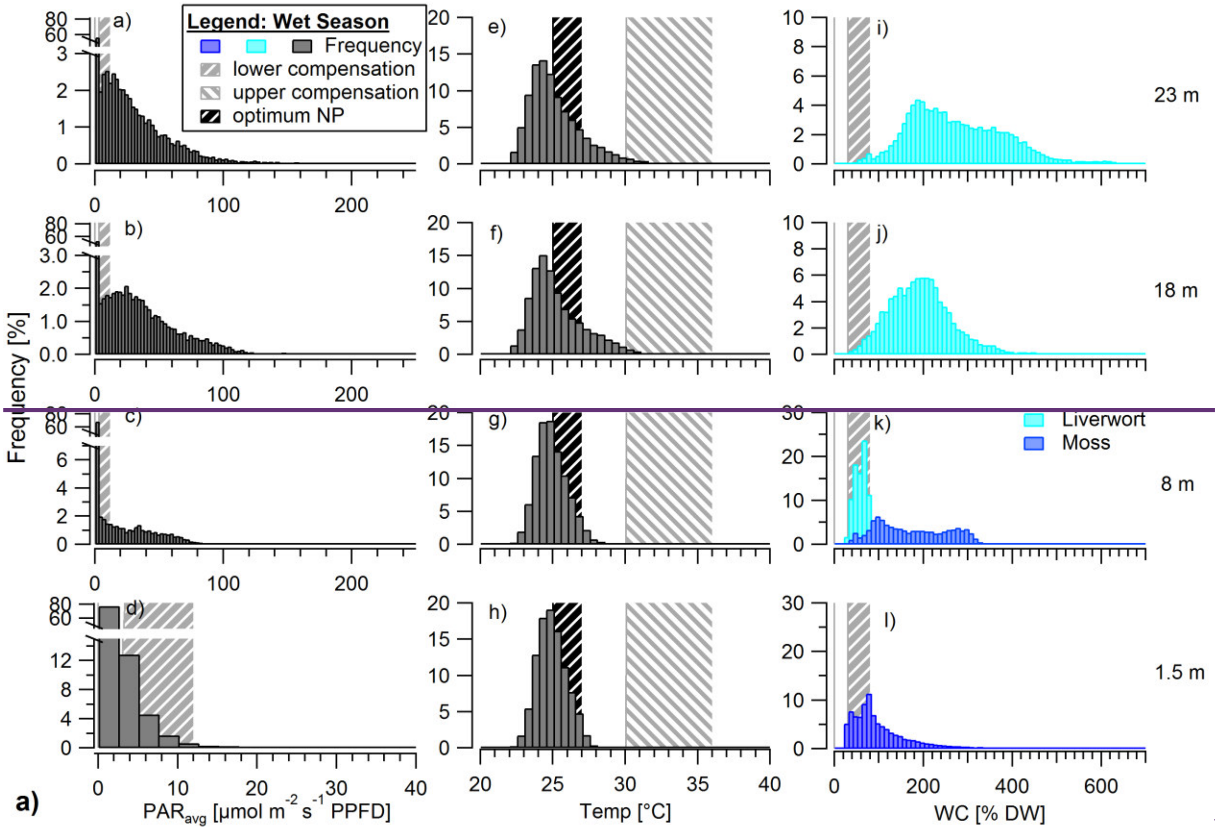
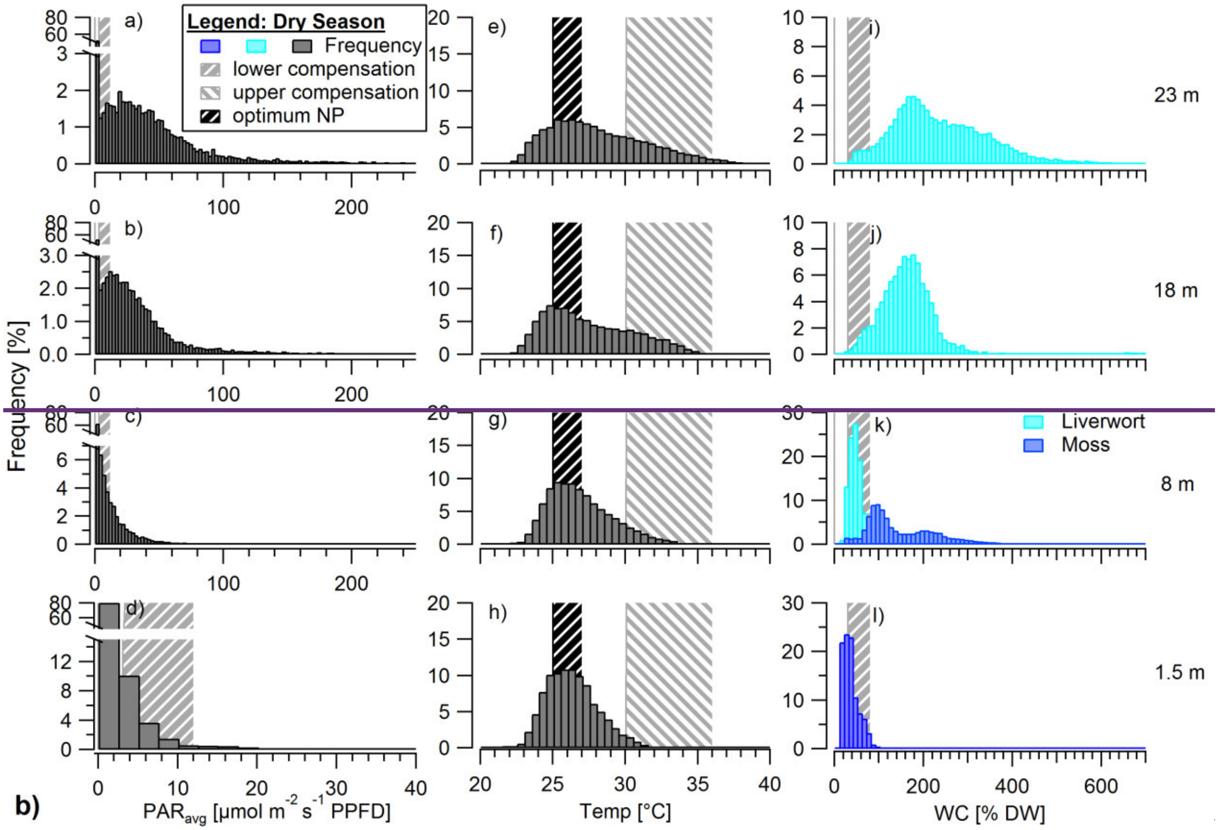
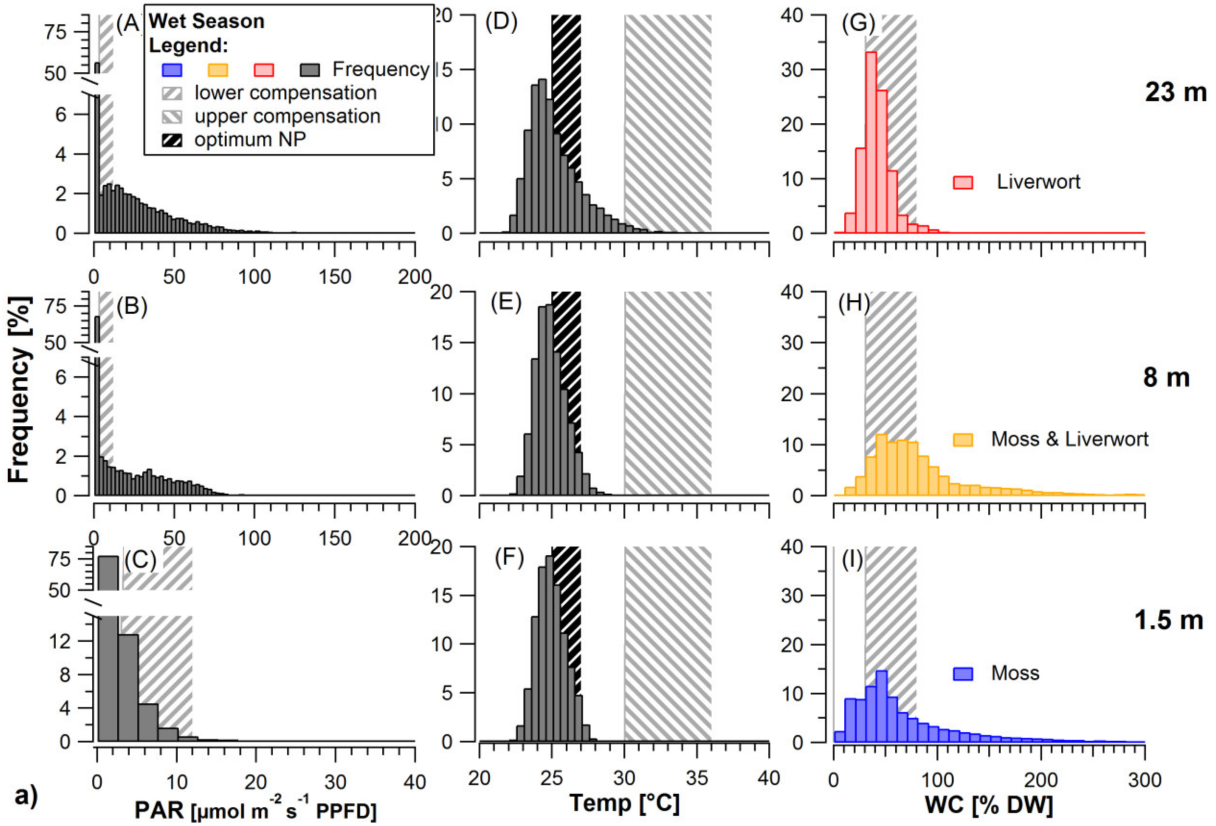


Figure 3: Mean diurnal cycles of light conditions (PAR~~$_{avg}$~~), temperature, and water content (WC) of bryophytes, and above-canopy meteorological parameters during (a) wet season and (b) dry season of the years 2015 (blue lines) and 2016 (green lines). The above-canopy meteorological parameters comprise (A) the photosynthetically active radiation (PAR~~$_{avg}$~~ at 75 m), (E~~F~~) the temperature (at 26 m), and (I~~K~~) the relative air humidity (RH at 26 m height). The micrometeorological parameters measured on top/within epiphytic cryptogamic communities comprise (B – D~~E~~) the photosynthetically active radiation (PAR) on top, (D~~G~~ – ~~J~~H) the temperature within, and (J~~L~~ – L~~O~~) the WC of cryptogamic communities at different height levels. Diel cycles were calculated from 30-minute intervals of the whole seasons and show hourly mean values ± SD. Data of the sensors installed at the same height level were pooled, while the above-canopy parameters were measured with one sensor each. ~~For the WC at 8 m height data of the mosses and liverwort samples are shown.~~ Nighttime is shaded in grey (06:00 – 18:00 LT).


Legend: Wet Season
Frequency
lower compensation
upper compensation
optimum NP
a)
b)
c)
d)
e)
f)
g)
h)
i)
j)
k)
l)
23 m
18 m
8 m
1.5 m
Liverwort
Moss
Frequency [%]
0
1
2
3
60
80
0.0
1.0
2.0
3.0
4
6
8
12
14
5
10
15
20
25
30
100
200
400
600
35
40
a)
PAR$_{avg}$ [µmol m^{-2} s^{-1} PPFD]
Temp [°C]
WC [% DW]


Legend: Dry Season
Frequency
lower compensation
upper compensation
optimum NP
a)
b)
c)
d)
e)
f)
g)
h)
i)
j)
k)
l)
23 m
18 m
8 m
1.5 m
Liverwort
Moss
Frequency [%]
PAR$_{avg}$ [µmol m^{-2} s^{-1} PPFD]
Temp [°C]
WC [% DW]
80
60
3
2
1
0
3.0
2.0
1.0
0.0
6
4
14
12
8
100
200
20
15
10
5
30
35
40
25
400
600

b)


Wet Season
Legend:
Frequency
lower compensation
upper compensation
optimum NP
(A)
(B)
(C)
(D)
(E)
(F)
(G)
(H)
(I)
23 m
8 m
1.5 m
Liverwort
Moss & Liverwort
Moss
Frequency [%]
a)
PAR [µmol m-2 s-1 PPFD]
Temp [°C]
WC [% DW]
0
50
100
150
200
10
20
30
40
25
35
300
75
6
4
2
12
8
15
5

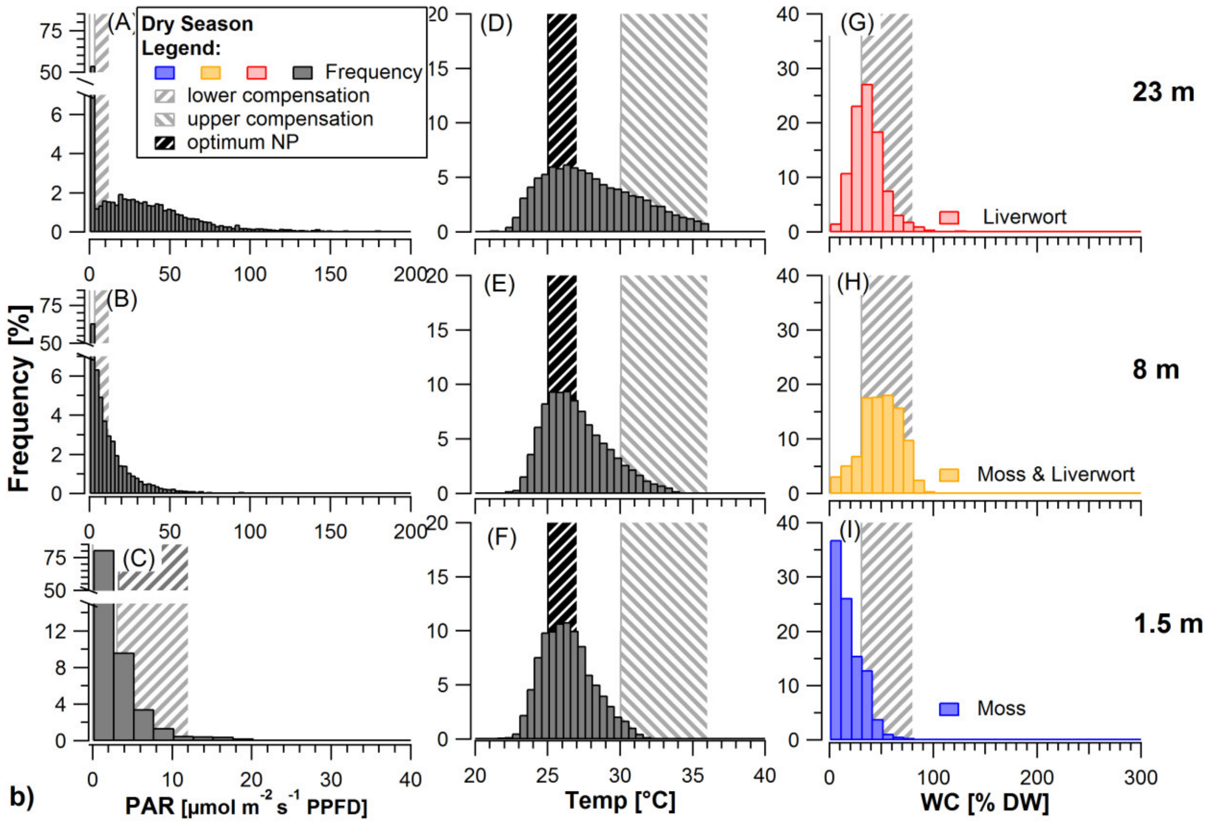


Figure 4: Estimated ~~F~~frequency of mean photosynthetically active radiation (PAR~~avg~~; A~~a~~ – C~~d~~), temperature (Temp; D~~e~~ – F~~h~~), and water content (WC; G~~i~~ – I~~l~~) measured on top/within bryophytes at 1.5, 8,~~ 18,~~ and 23 m height during (a) the wet and (b) the dry season. Calculation of the histograms based on 30-minute intervals. Shaded areas represent the ranges of reference values for lower compensation (PAR, WC), upper compensation (temperature), and the optimum (temperature) for net photosynthesis, as measured by~~. Value ranges are adopted from~~ Lösch (1994) and Wagner et al., (2013) (Table ~~S5~~S4). Bin sizes: PAR: 2.5 µmol m^{-2} s^{-1}; temperature: 0.5 °C; WC: 10 %.

Microclimatic conditions and water content fluctuations experienced by epiphytic bryophytes in an Amazonian rain forest

Contents:

Figures S1 – S10

Tables S1 – S7~~6~~

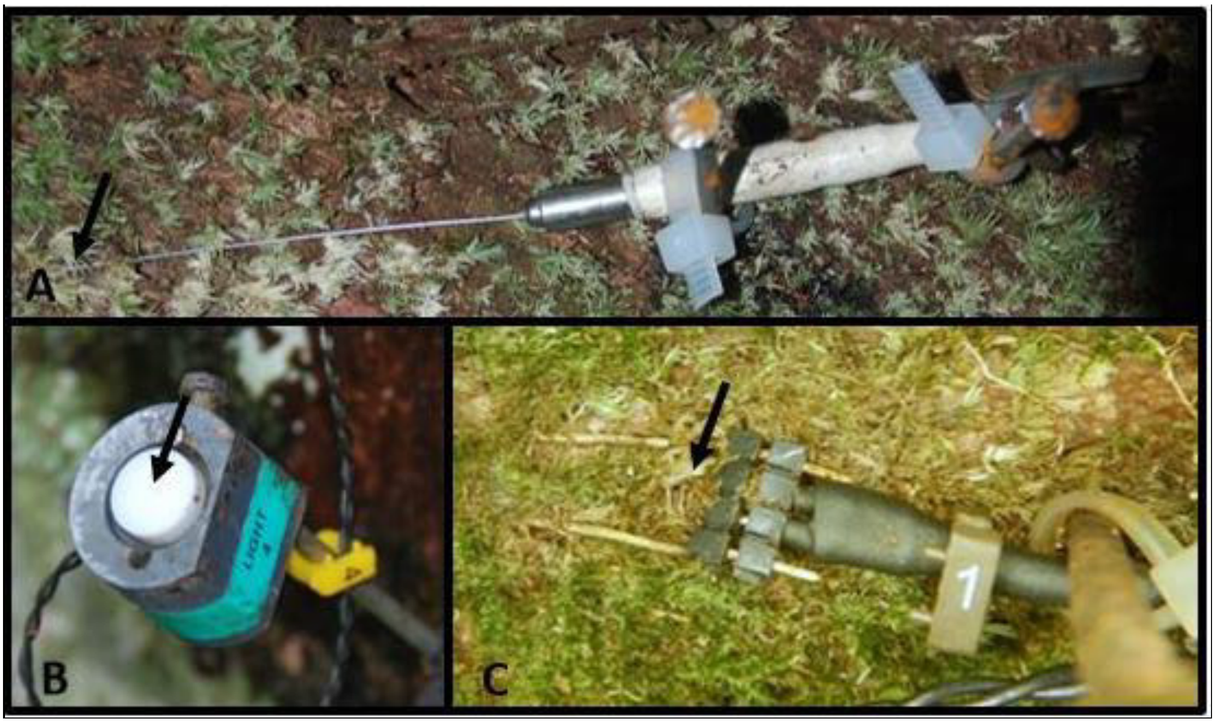
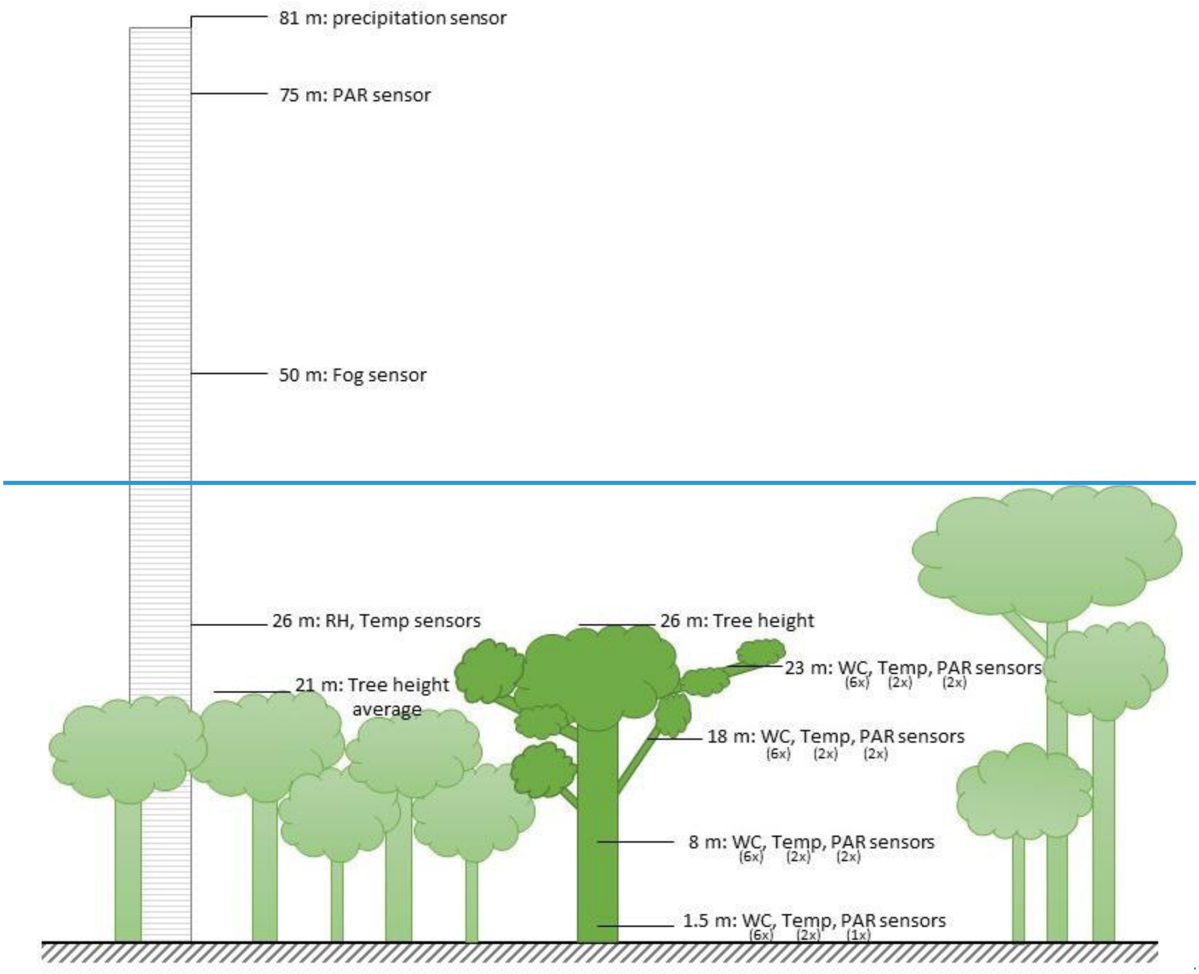


Figure S1: Examples of the temperature sensor (A), light sensor (B), and water content sensor (C) installed in epiphytic bryophytes at the ATTO site. The little arrows show the area of detection, i.e. the sensor tip of the temperature sensor, the area just below the white PTFE cap of the light sensor, and the two inner pins of the water content sensor.


81 m: precipitation sensor
75 m: PAR sensor
50 m: Fog sensor
26 m: RH, Temp sensors
21 m: Tree height average
26 m: Tree height
23 m: WC, Temp, PAR sensors
(6x) (2x) (2x)
18 m: WC, Temp, PAR sensors
(6x) (2x) (2x)
8 m: WC, Temp, PAR sensors
(6x) (2x) (2x)
1.5 m: WC, Temp, PAR sensors
(6x) (2x) (1x)

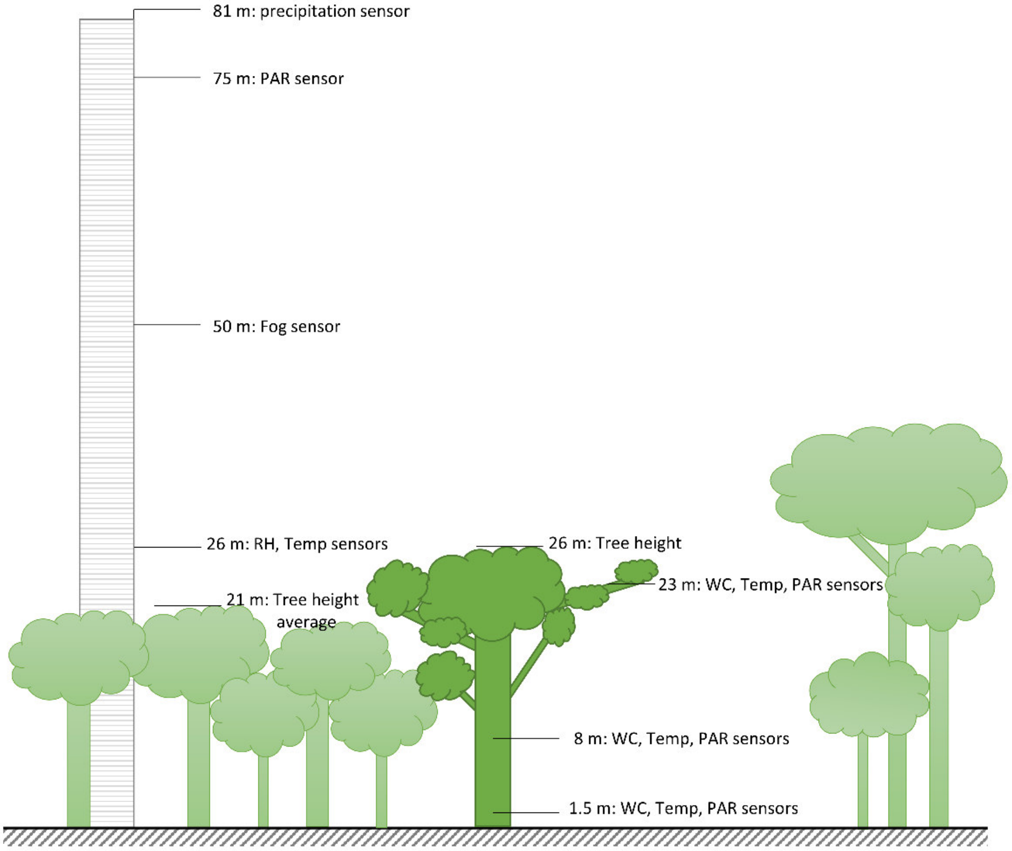


Figure S2: Schematic overview of the sensors installed at different height levels below, within, and above the canopy. The parameters water content (WC) and temperature (Temp) were measured within the bryophyte samples, the light sensors (PAR) were installed directly on top of the thalli. The average tree height of 21 m was determined for the Plateau forest in general.

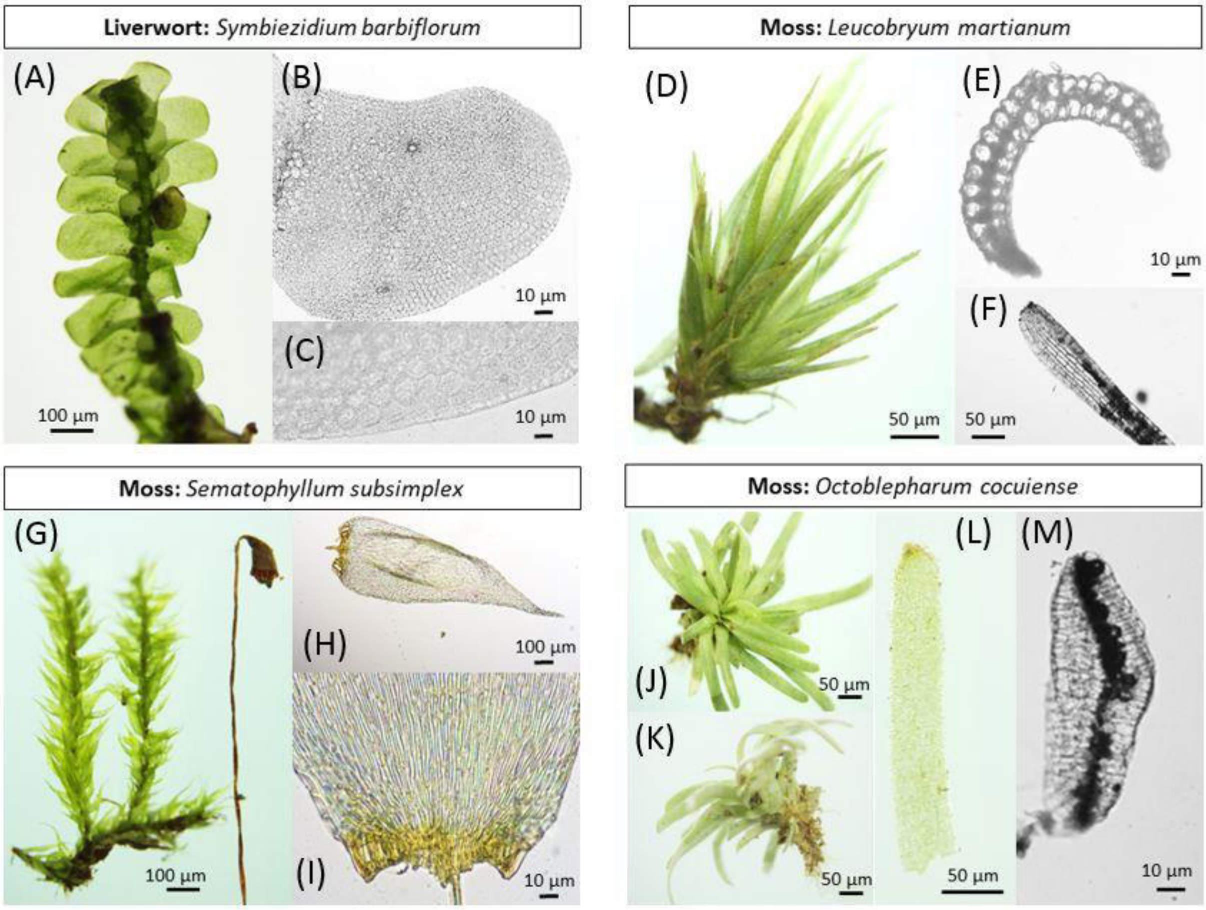
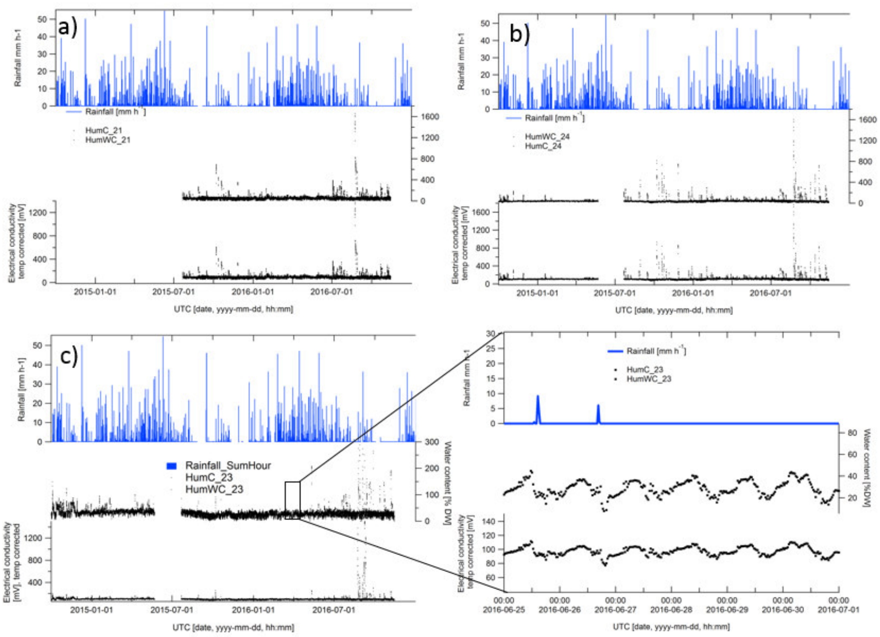


Figure S3: The four bryophyte species being used for installation of the sensors of the microclimate station. (A, D, G, J, K) overview, (B, H, L) leaf, (C, F I) cell form, and (E, M) cross section of a leaf.

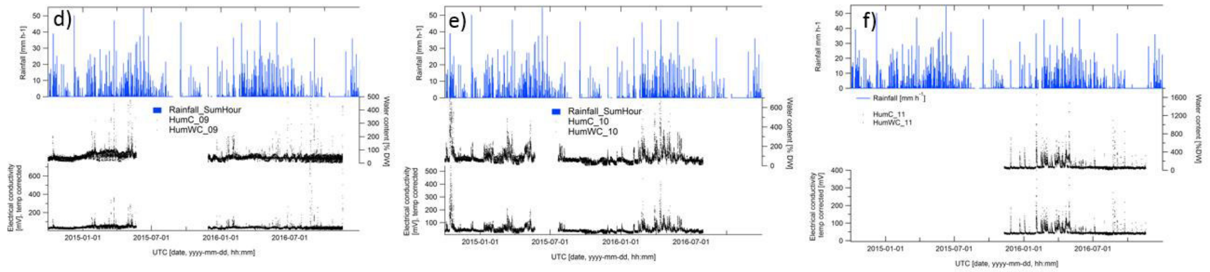

Upper side of the branch
23 m
Inclinated on the branch
18 m
Along the trunk
8 m
Along the trunk
1.5 m

Figure S4: Overview pictures of microsensor tree and exemplary bryophyte samples with installed water content sensors at the four height levels.

Sensors at 23 m height level (inner canopy)



Sensors at 8 m height level (stem)



Sensors at 1.5 m height level (understory)

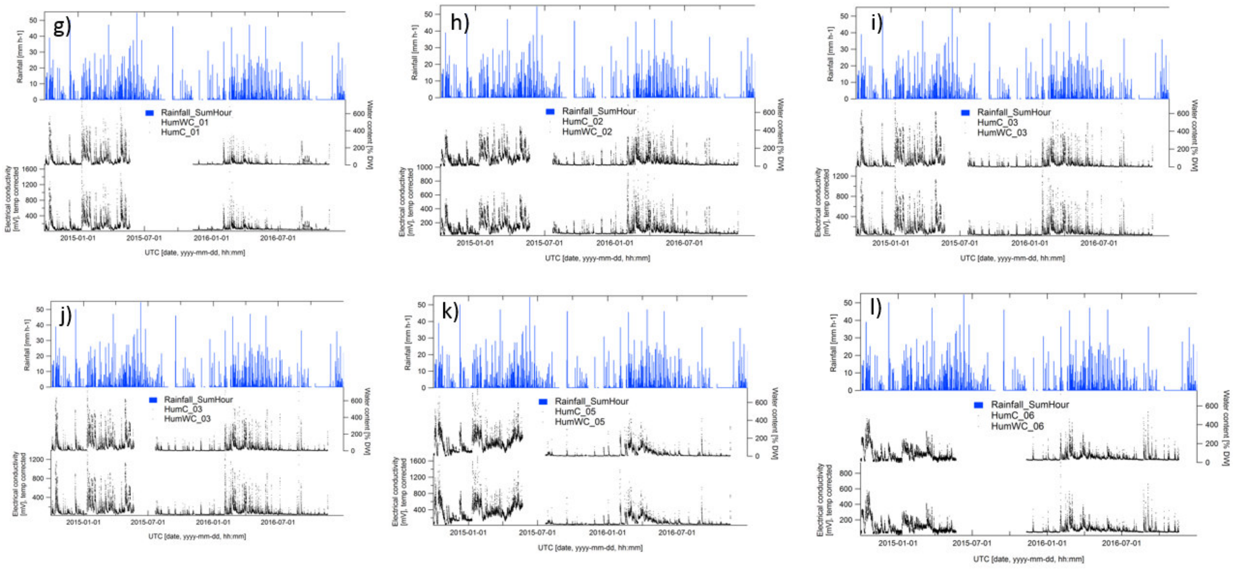
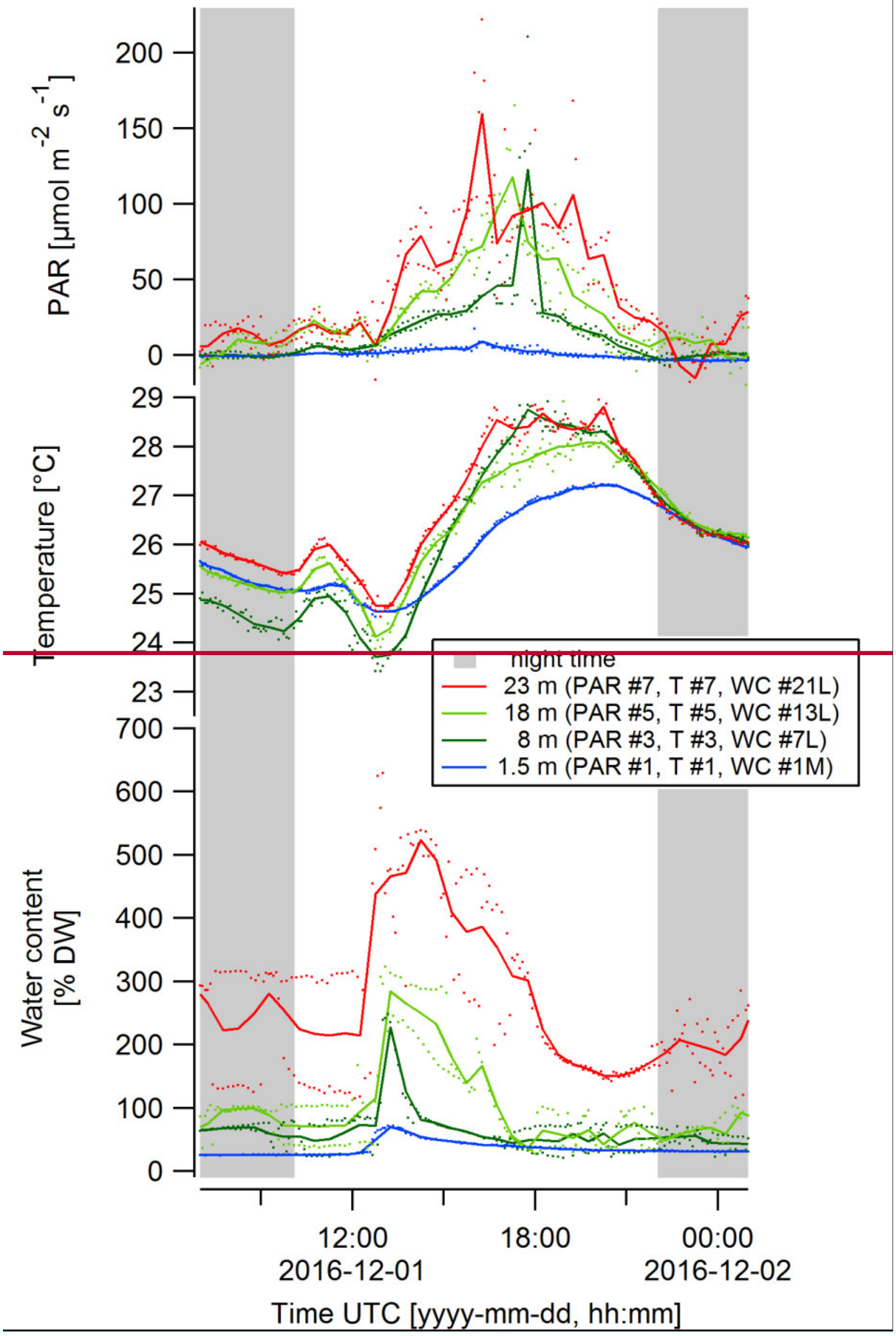
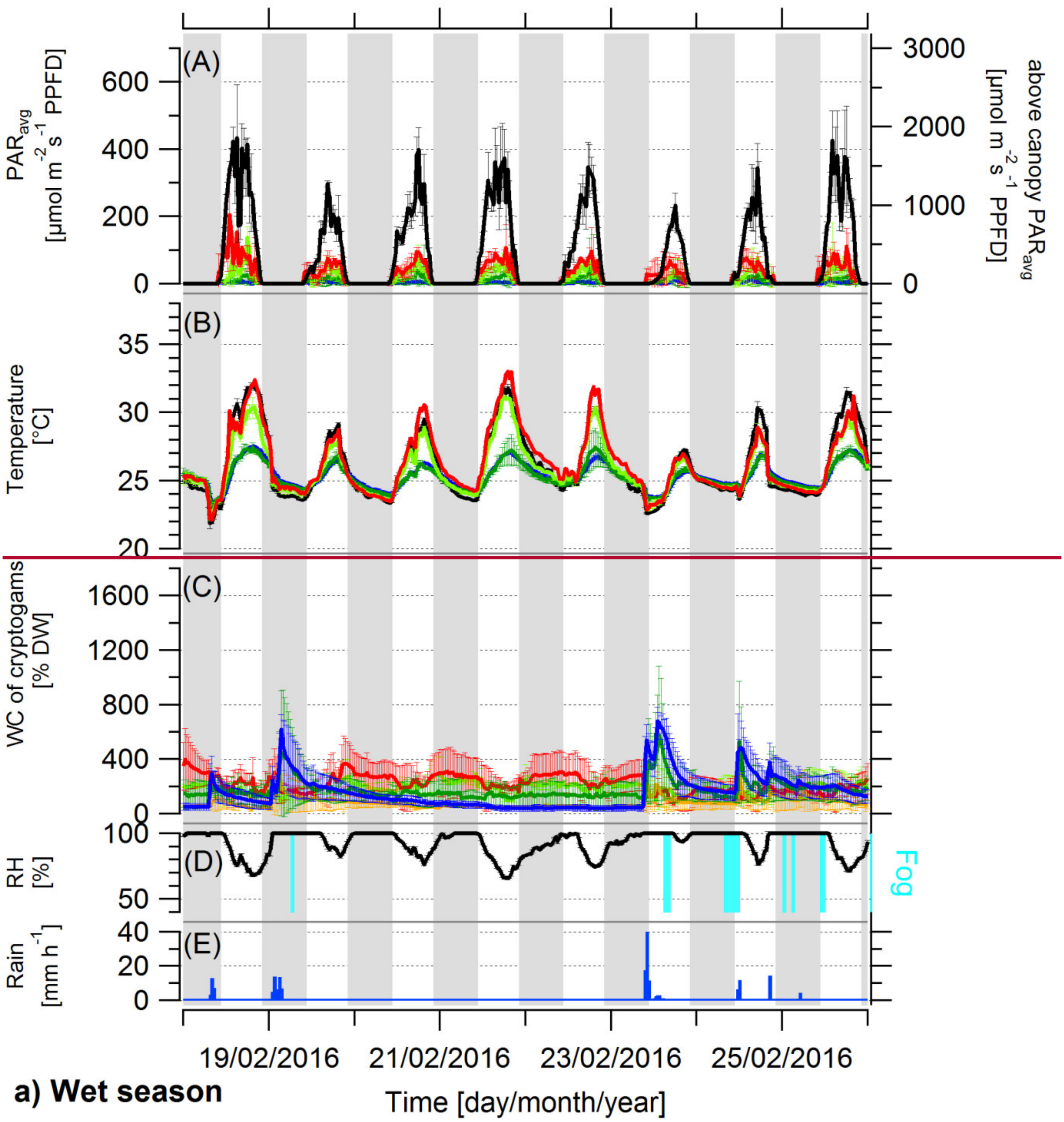


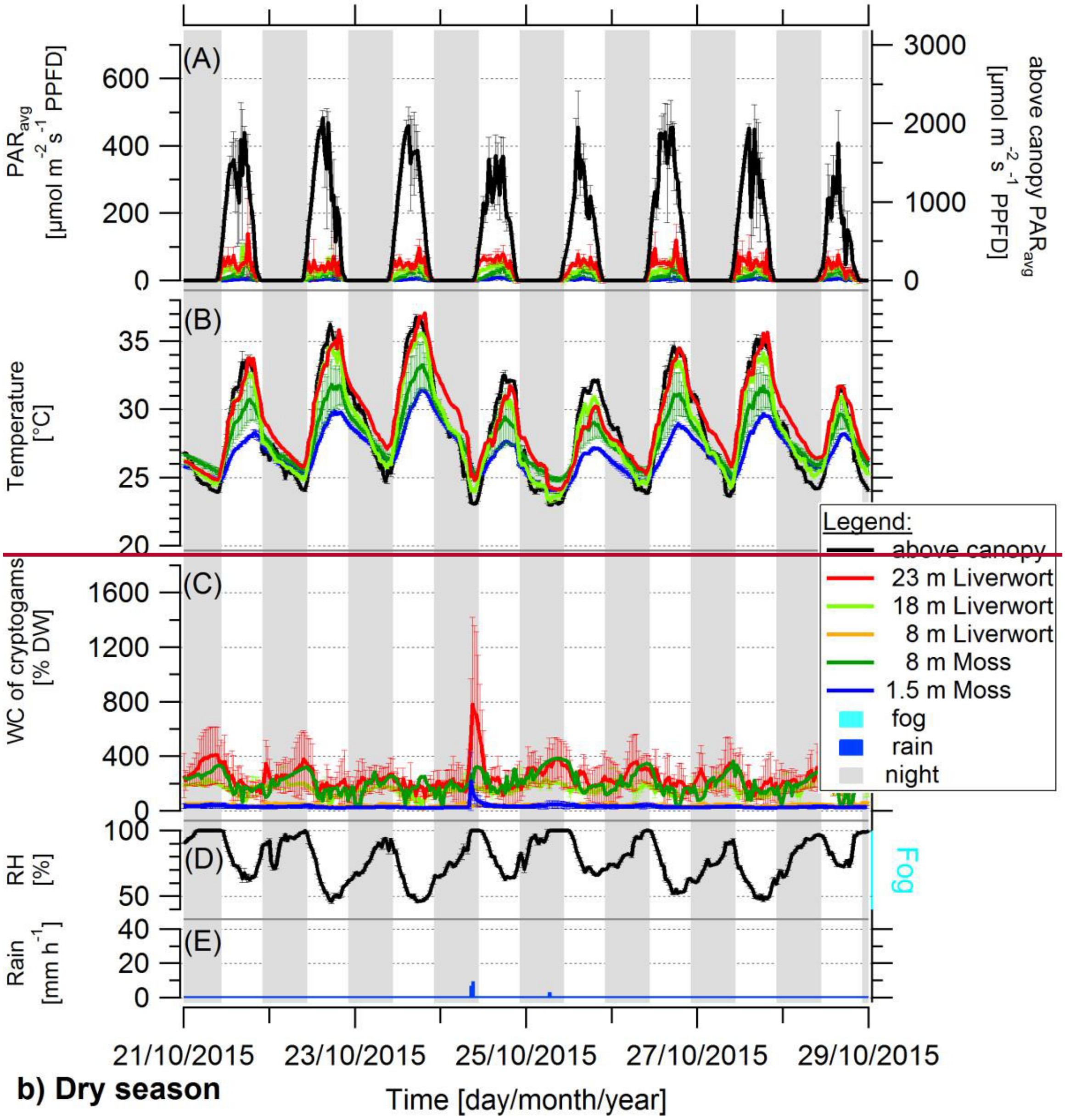
Figure S5. Long-term measurements of precepitation, electrical conductivity, and the calculated water content. All the sensors utilized for further calculations are shown: (a, b, c) at 23 m height, (d, e, f) at the 8 m height, and (g, h, i, j, k, l) at 1.5 m height. Gaps in the dataset correspond to maintenance periods.



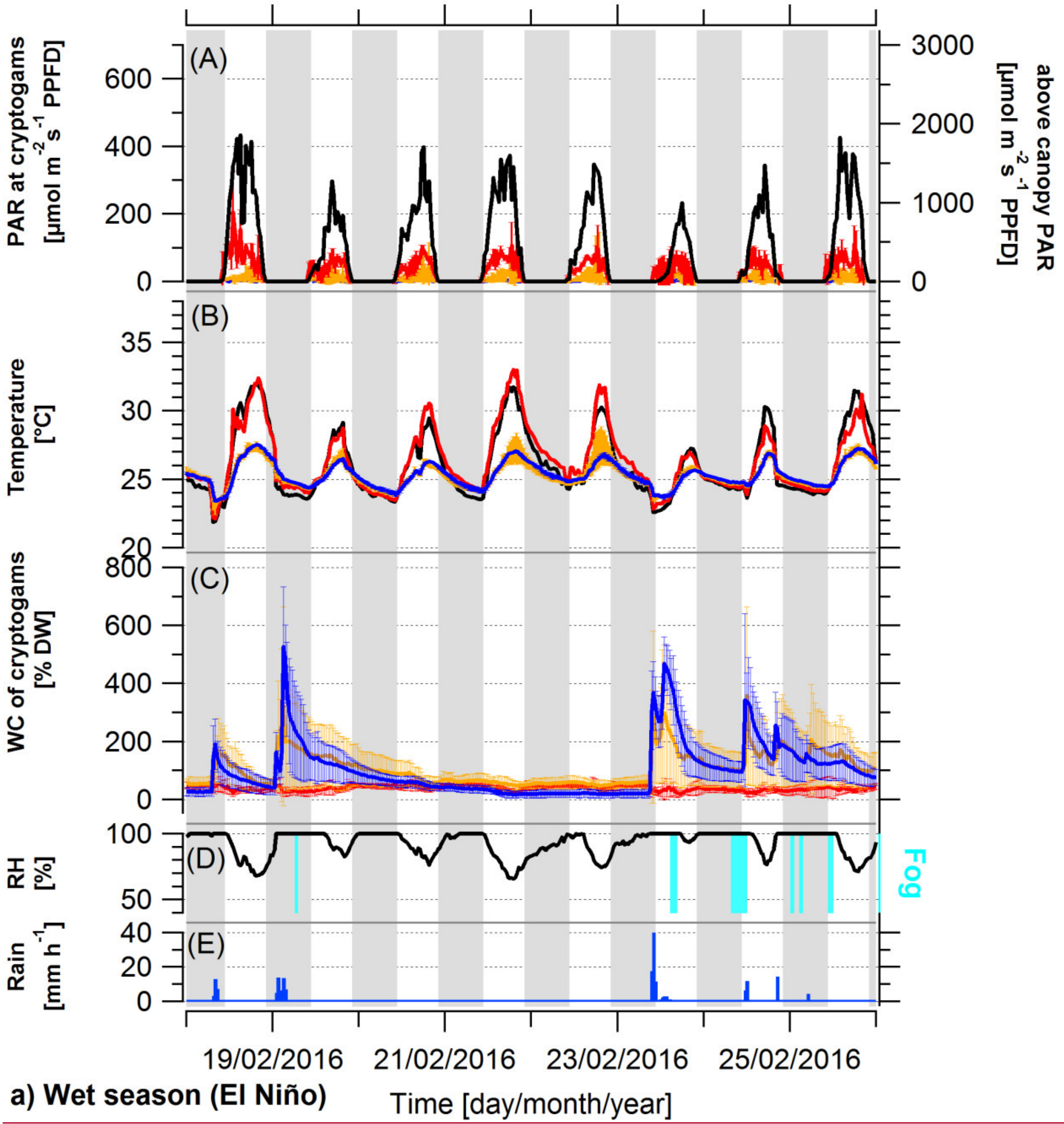
~~**Figure S5:** Comparison of 5-minute (dots) and 30-minute (lines) averages of exemplary sensors at each height level over a period of approx. one day in December 2016.~~ 5


(A)
PAR$_{avg}$ [µmol m^{-2} s^{-1} PPFD]
0
200
400
600
above canopy PAR$_{avg}$ [µmol m^{-2} s^{-1} PPFD]
0
1000
2000
3000
(B)
Temperature [°C]
20
25
30
35
(C)
WC of cryptogams [% DW]
0
400
800
1200
1600
(D)
RH [%]
50
100
Fog
(E)
Rain [mm h^{-1}]
0
20
40
19/02/2016
21/02/2016
23/02/2016
25/02/2016
Time [day/month/year]

a) Wet season


(A)
PAR$_{avg}$ [µmol m^{-2} s^{-1} PPFD]
0
200
400
600
above canopy PAR$_{avg}$ [µmol m^{-2} s^{-1} PPFD]
0
1000
2000
3000
(B)
Temperature [°C]
20
25
30
35
(C)
WC of cryptogams [% DW]
0
400
800
1200
1600
(D)
RH [%]
50
100
Fog
(E)
Rain [mm h^{-1}]
0
20
40
21/10/2015
23/10/2015
25/10/2015
27/10/2015
29/10/2015
Time [day/month/year]
Legend:
above canopy
23 m Liverwort
18 m Liverwort
8 m Liverwort
8 m Moss
1.5 m Moss
fog
rain
night

b) Dry season



a) Wet season (El Niño)

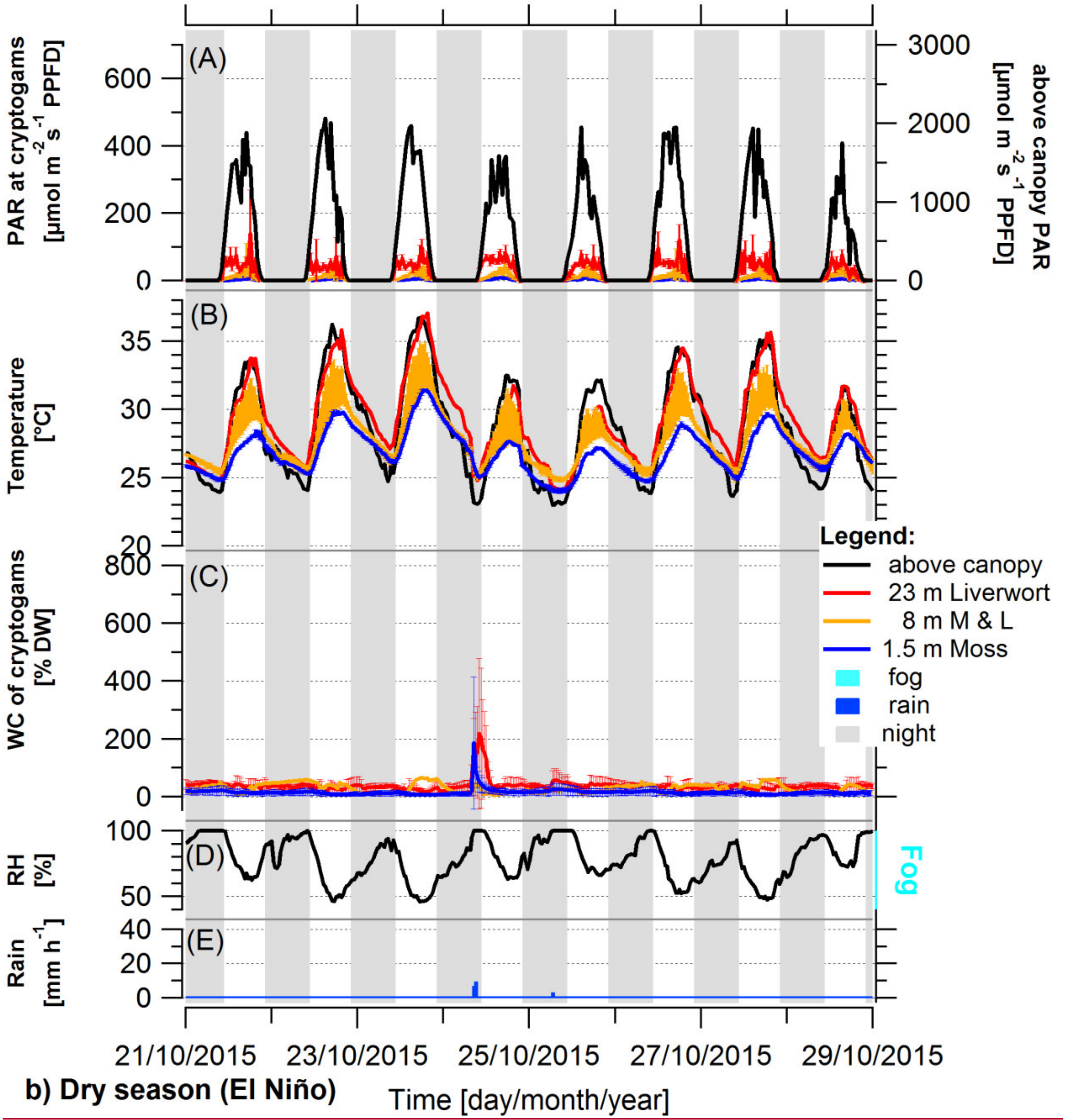
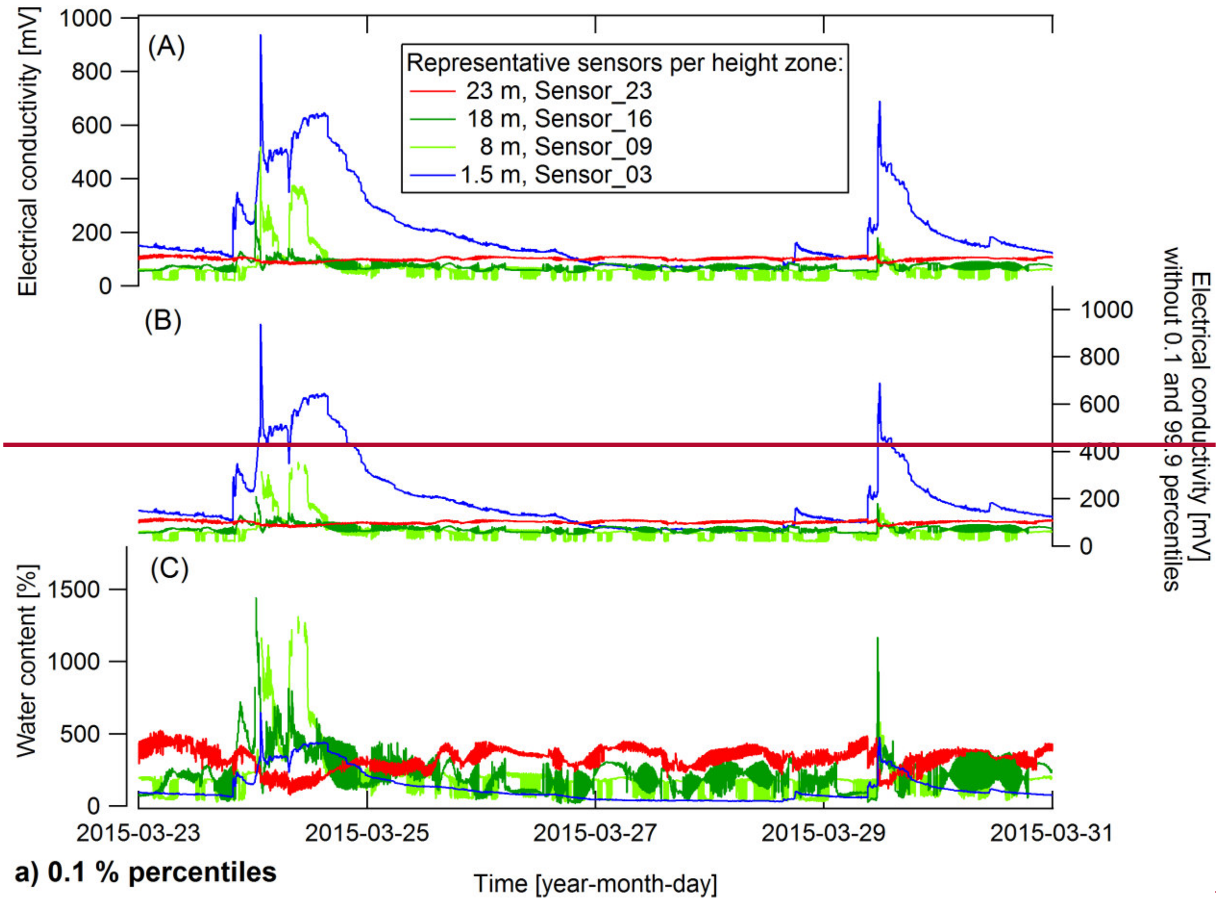
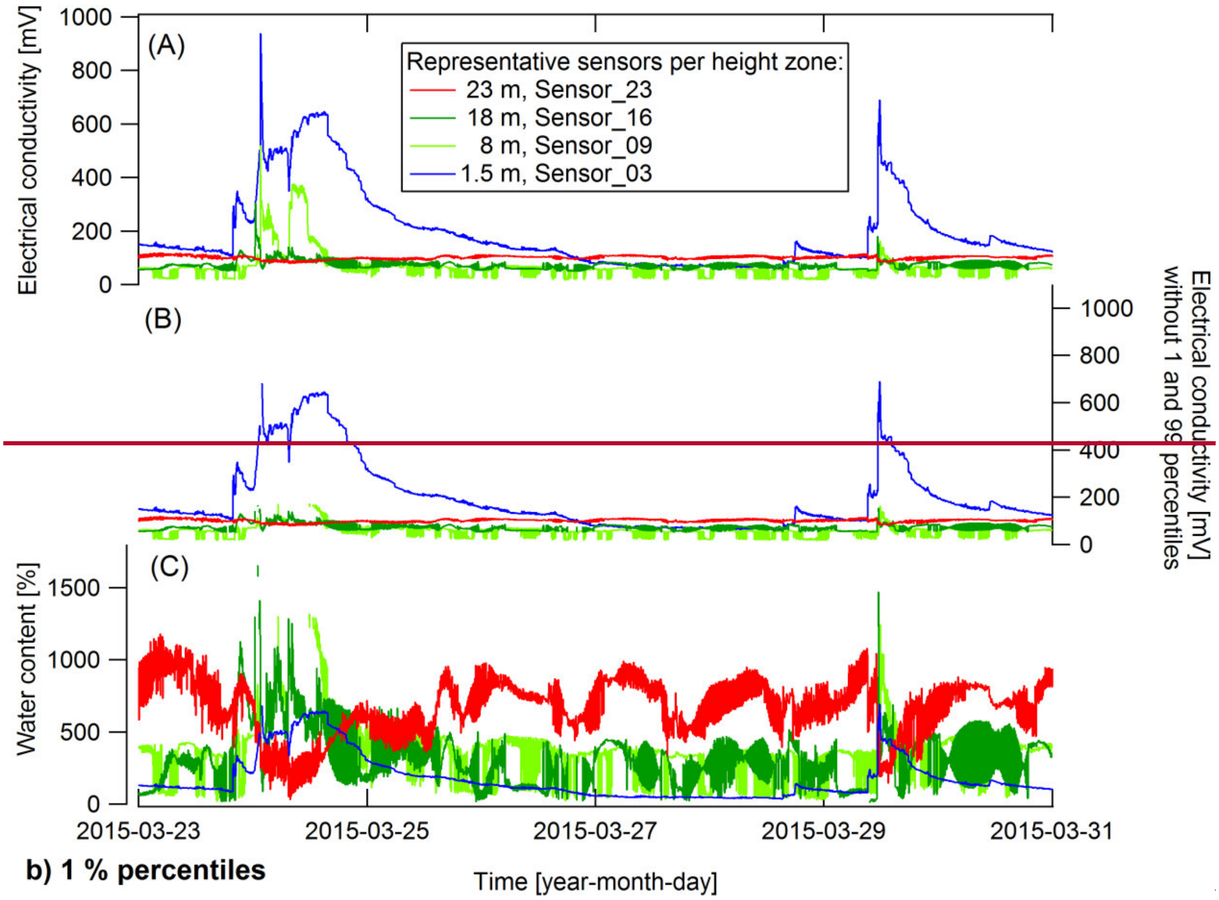


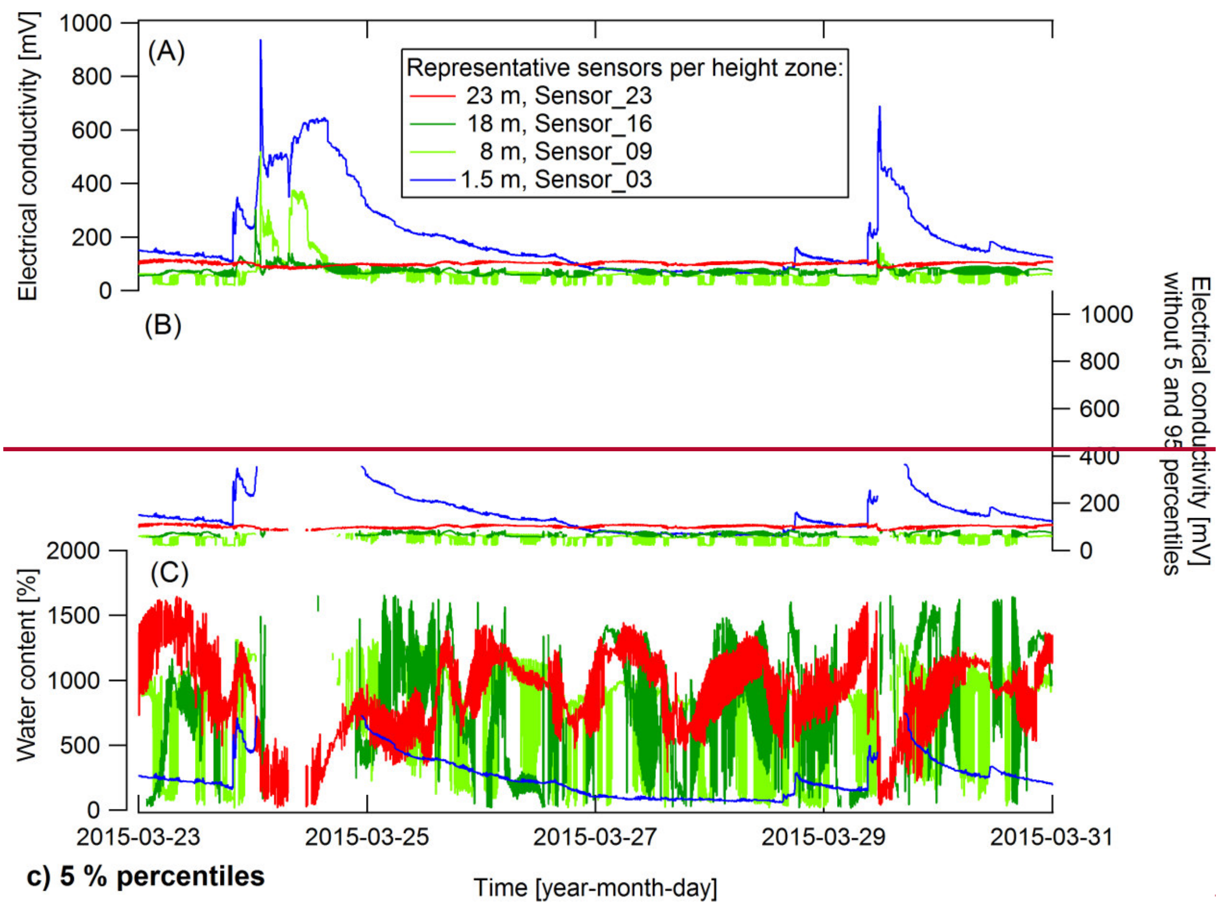
Figure S6: Representative periods during wet and dry season under the influence of El Niño, showing light conditions (PAR~~$_{\mathrm{avg}}$~~), temperature, and water content (WC) experienced by bryophytes, and above-canopy meteorological conditions in the Amazonian rain forest. Shown are 8-day periods during a) the wet season 2016 and b) the dry season 2015. The micrometeorological parameters on top/within epiphytic cryptogamic communities represent (A) the photosynthetically active radiation (PAR~~$_{\mathrm{avg}}$~~) on top, (B) the temperature within, and (C) the water content of cryptogamic communities. The above-canopy meteorological parameters comprise (A) the above-canopy photosynthetically active radiation (PAR~~$_{\mathrm{avg}}$~~ at 75 m), (B) the above-canopy temperature (at 26 m), (D) the relative air humidity (RH at 26 m), the presence of fog events, and (E) the rain amount. The data show 30-minute averages ± SD except for rain, which shows hourly sums. Data of replicate sensors installed within communities at the same height level were pooled, while above-canopy parameters were measured with one sensor each. The nighttime is shaded in grey color (06:00 – 18:00 LT).



a) 0.1 % percentiles



b) 1 % percentiles



c) 5 % percentiles

~~Figure S7: Exemplary snapshots of the conversion from (A) the measured electrical conductivity, via (B) the electrical conductivity minus the upper and the lower percentiles, to (C) the water content of the epiphytic bryophytes. The figures show a) the finally chosen 0.1 % percentiles, b) the 1 % percentiles, and c) the 5 % percentiles. The same time frame as in Figure 2a) was chosen. Data shown as 5 minute average.~~

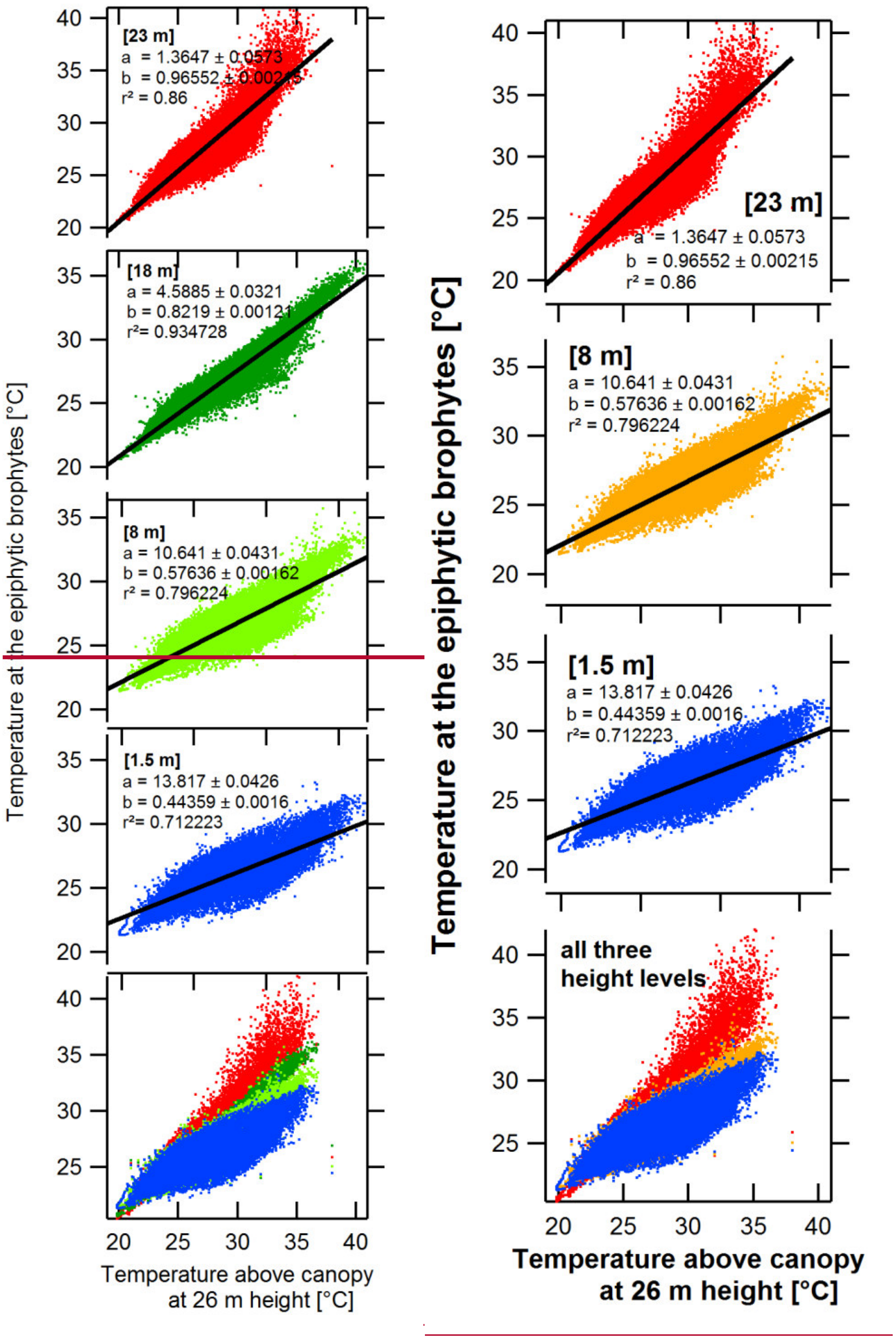


Figure ~~S8~~S7: Temperature within bryophytes compared to the above-canopy temperature. The temperature within bryophytes was measured at 1.5 m, 8 m, ~~18 m,~~ and 23 m, while the above-canopy temperature was measured at 26 m height on the tower. The data are presented per height zone and also pooled together in the lowest panel. Data present 30-minute averages with linear fits, of the function y = a + bx, with the coefficients (± 1 std. dev.) and the R² are given in the figure for each height level.

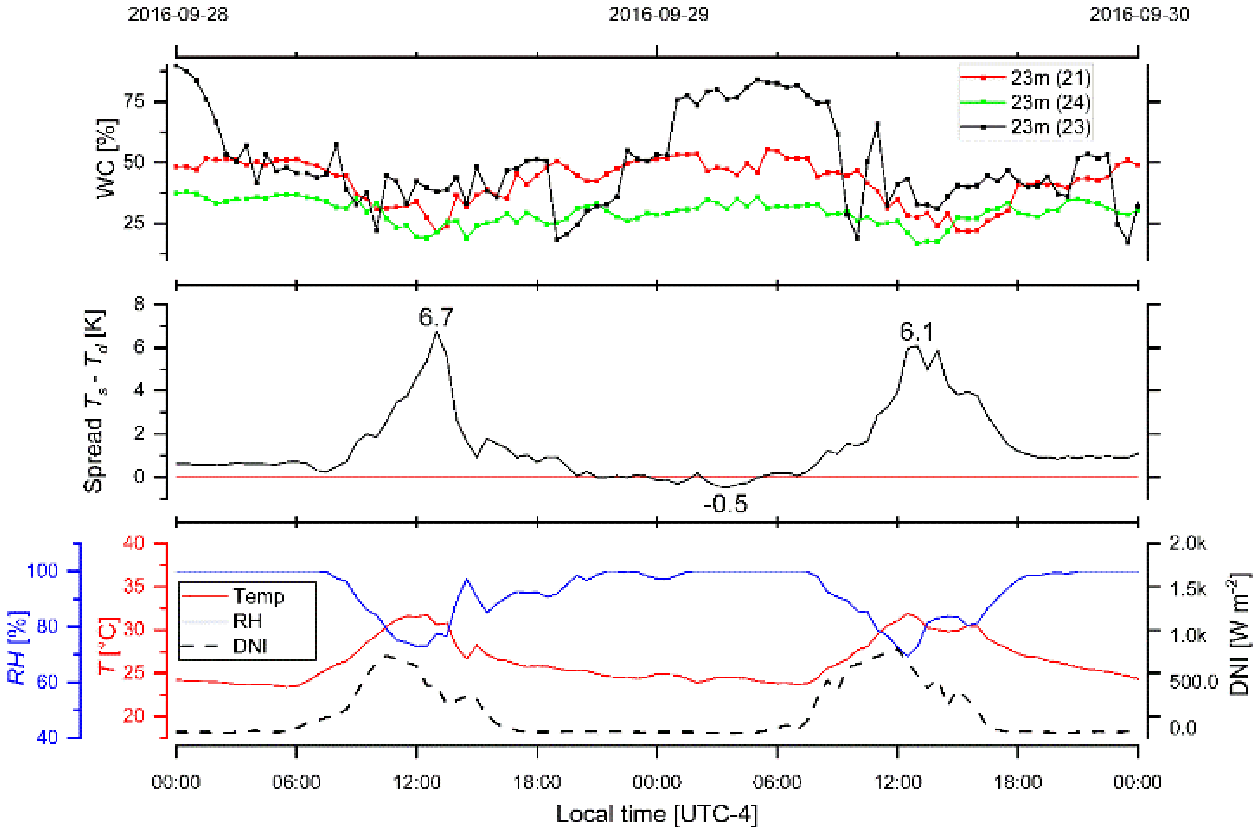


Figure S8: Exeplary daily (micro-)climatic conditions at the canopy level, showing the WC values of the 3 sensorsat 23m [%] (A), the dew point spread at 23 m [°C] (B), and the environmental factors relative humidity RH[%], temperature T [°C] and direct normal irradiance DNI [W m^{-2}] measured at 26 m (C). 5

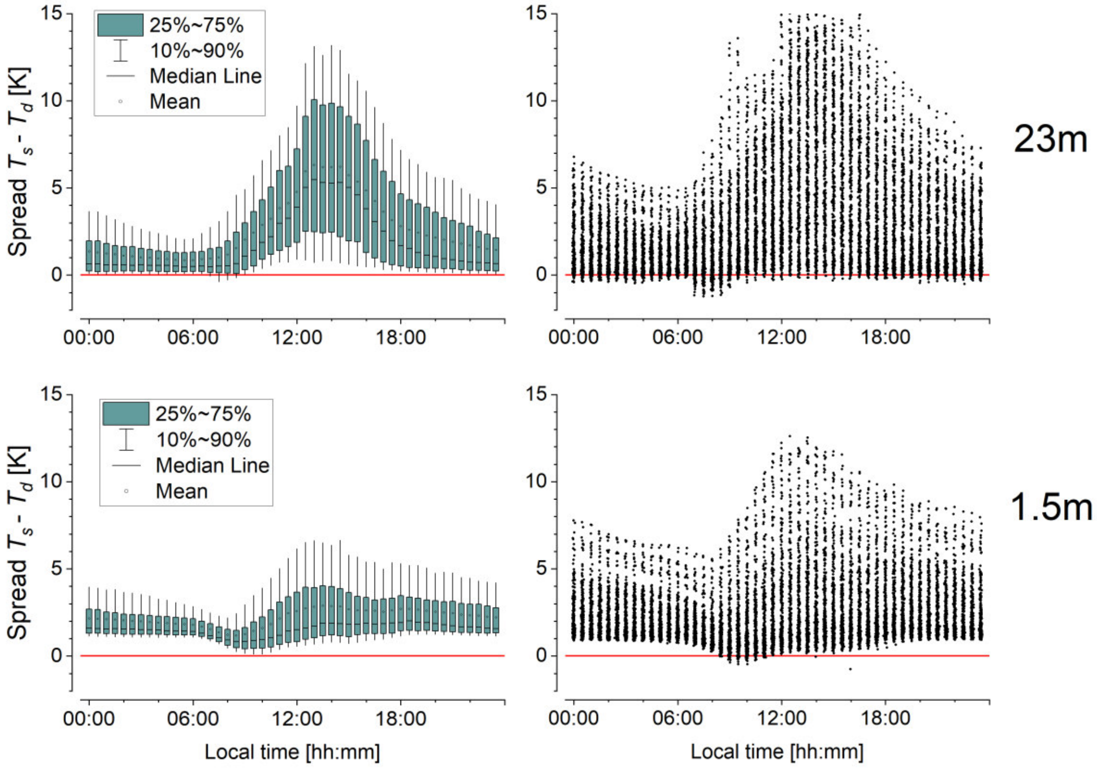
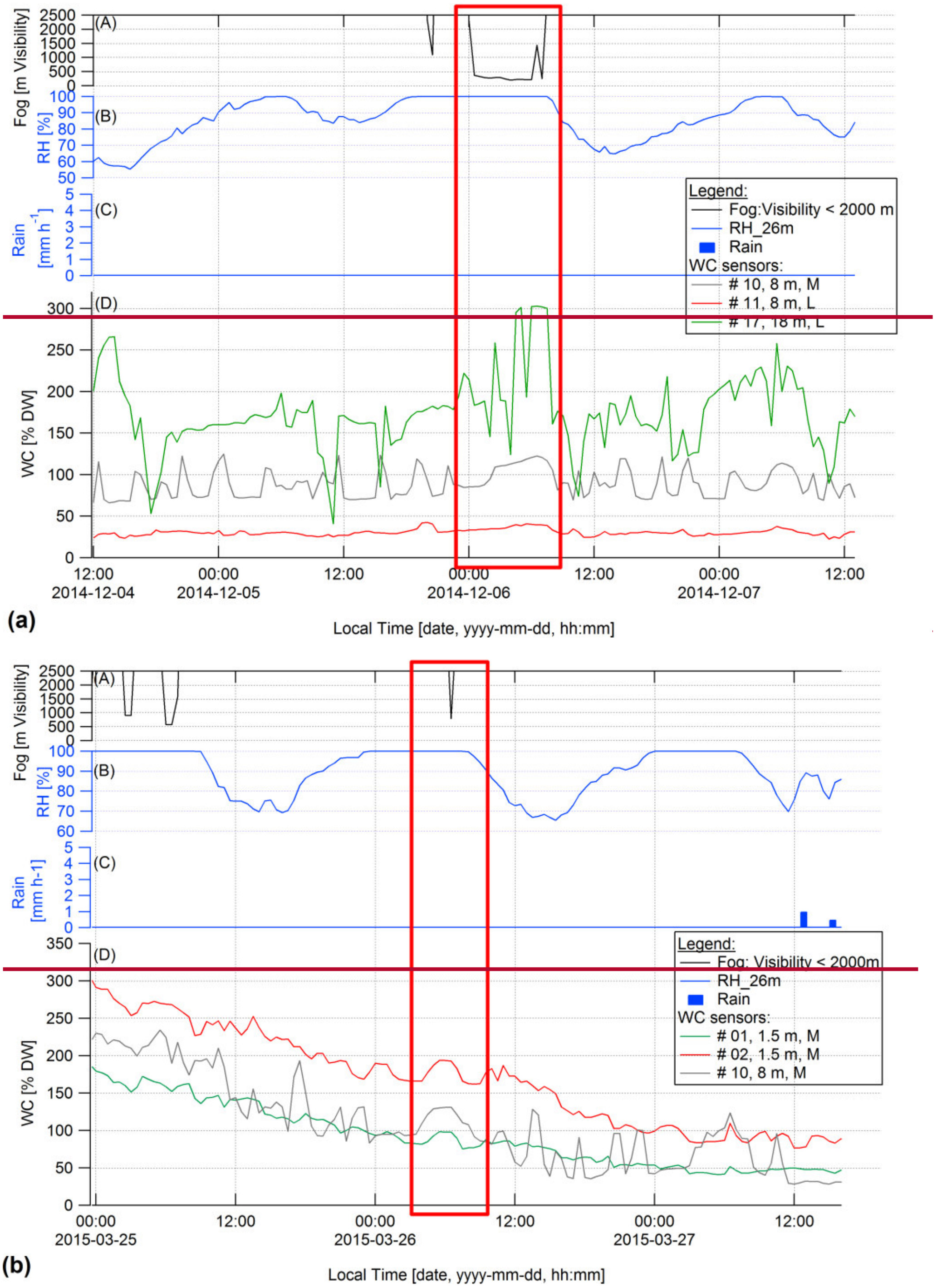


Figure S9: Diel dew point spread at 1.5 m and 23 m height levels in a 24h cycle, illustrating the difference between the temperature of the substrate (T_s) and the dew point of the surrounding air (T_d). ~~In case~~If the suface temperature is lower than the dew point of the surrounding air (values below red line), condensation might occur.



~~**Figure S9:** Two exemplary fog events and the reaction of the moisture sensors of the bryophytes (a and b). Each panel presents (A) a fog event with the parameters fog with visibility < 2000 m being defined as fog occurrence, (B) relative air humidity (RH), (C) rain, and (D) the water content (WC) of the bryophytes shown for some exemplary sensors. The fog event of interest is marked by a red box. For the WC sensors the number, height of installation, and division (M = Moss, L = Liverwort) are given. Data presented as 30 minute averages.~~

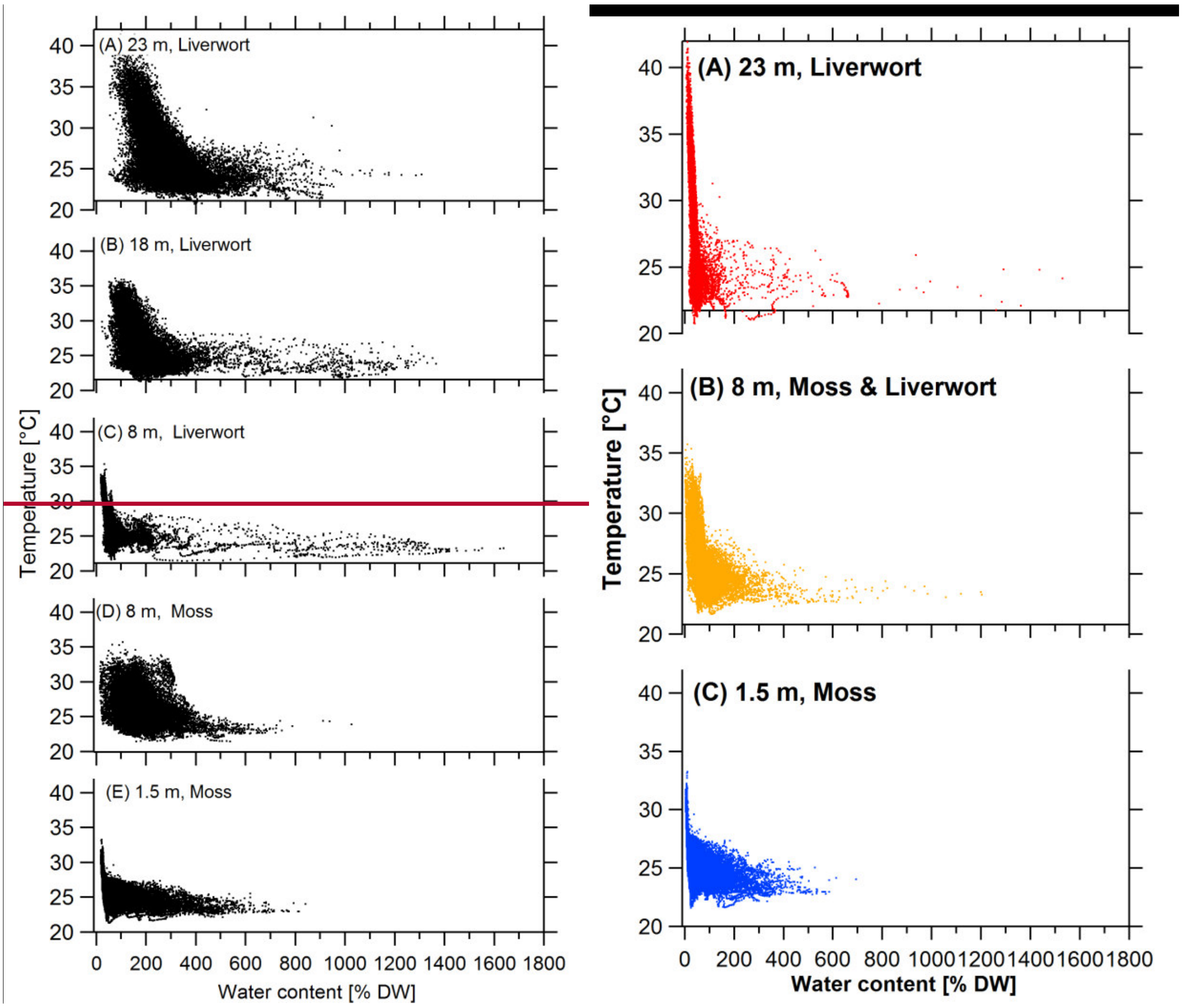


Figure S10: Temperature conditions of bryophytes related to their water content. The temperature was measured in bryophytes at different height levels along the tree. Data presented as 30-minute averages.

Table S1: Height of installation, minimum and maximum values of the individual sensors of the microclimate station measuring water content, temperature, and light. For the water content sensors, also the bryophyte species are given. ~~For calibration of the water content sensors, the uppermost and lowermost 0.1% of the electrical conductivity values were not considered (see method section for further details)~~ Based on 30-minute averages.

Sensor No	**Height [m]**	**Water content [% DW]**		**Bryophyte species**	**Sensor No**	**Height [m]**	**Temperature [°C]**	
		min	**max**				**min**	**max**
Sensor 01	1.5	0	763	*Sematophyllum subsimplex*	Sensor 01	1.5	21.1	36.3
Sensor 02	1.5	0	763	*Sematophyllum subsimplex*	Sensor 02	1.5	21.4	39.4
Sensor 03	1.5	0	763	*Sematophyllum subsimplex*	Sensor 03	8	21.6	34.7
Sensor 04	1.5	0	1373	*Leucobryum martianum*	Sensor 04	8	20.9	46.3
Sensor 05	1.5	0	763	*Sematophyllum subsimplex*	Sensor 07	23	20.8	41.2
Sensor 06	1.5	0	763	*Sematophyllum subsimplex*	Sensor 08	23	20.3	48.7
Sensor 09	8	0	1318	*Octoblepharum cocuiense*		**Height [m]**	**PAR [µmol m^{-2} s^{-1}]**	
Sensor 10	8	0	1318	*Octoblepharum cocuiense*				
Sensor 11	8	0	1658	*Symbiezidium barbiflorum*			**min**	**max**
Sensor 21	23	0	1658	*Symbiezidium barbiflorum*	Sensor 01	1.5	0	634
Sensor 23	23	0	1658	*Symbiezidium barbiflorum*	Sensor 02	8	0	569
Sensor 24	23	0	1658	*Symbiezidium barbiflorum*	Sensor 03	8	0	1121
					Sensor 06	23	0	654
					Sensor 07	23	0	767

~~**Water content**~~	~~**Height [m]**~~	~~**WC [% DW]**~~		~~**Bryophyte species**~~	~~**Temperature**~~	~~**Height [m]**~~	~~**Temperature [°C]**~~	
		~~**min (0.1%)**~~	~~**max (99.9%)**~~				~~**min**~~	~~**max**~~
~~Sensor 01~~	~~1.5~~	~~14~~	~~762~~	~~*Sematophyllum subsimplex*~~	~~Sensor 01~~	~~1.5~~	~~21.1~~	~~36.3~~
~~Sensor 02~~	~~1.5~~	~~14~~	~~761~~	~~*Sematophyllum subsimplex*~~	~~Sensor 02~~	~~1.5~~	~~21.4~~	~~39.4~~
~~Sensor 03~~	~~1.5~~	~~13~~	~~761~~	~~*Sematophyllum subsimplex*~~	~~Sensor 03~~	~~8~~	~~21.6~~	~~34.7~~
~~Sensor 04~~	~~1.5~~	~~15~~	~~1368~~	~~*Leucobryum martianum*~~	~~Sensor 04~~	~~8~~	~~20.9~~	~~46.3~~
~~Sensor 05~~	~~1.5~~	~~13~~	~~760~~	~~*Sematophyllum subsimplex*~~	~~Sensor 05~~	~~18~~	~~20.3~~	~~38.0~~
~~Sensor 06~~	~~1.5~~	~~17~~	~~750~~	~~*Sematophyllum subsimplex*~~	~~Sensor 06~~	~~18~~	~~20.3~~	~~37.5~~
~~Sensor 07~~	~~8~~	~~16~~	~~1647~~	~~*Symbiezidium barbiflorum*~~	~~Sensor 07~~	~~23~~	~~20.8~~	~~41.2~~
~~Sensor 08~~	~~8~~	~~15~~	~~1311~~	~~*Octoblepharum cocuiense*~~	~~Sensor 08~~	~~23~~	~~20.3~~	~~48.7~~
~~Sensor 09~~	~~8~~	~~15~~	~~1302~~	~~*Octoblepharum cocuiense*~~		~~**Height**~~	~~**PAR**~~	
~~Sensor 10~~	~~8~~	~~16~~	~~1315~~	~~*Octoblepharum cocuiense*~~	~~**Light**~~	~~**[m]**~~	~~**[µmol m^{-2} s^{-1}]**~~	
~~Sensor 11~~	~~8~~	~~17~~	~~1649~~	~~*Symbiezidium barbiflorum*~~			~~**min**~~	~~**max**~~
~~Sensor 12~~	~~8~~	~~17~~	~~1639~~	~~*Symbiezidium barbiflorum*~~	~~Sensor 01~~	~~1.5~~	~~0~~	~~634~~
~~Sensor 13~~	~~18~~	~~19~~	~~1657~~	~~*Symbiezidium barbiflorum*~~	~~Sensor 02~~	~~8~~	~~0~~	~~569~~
~~Sensor 14~~	~~18~~	~~21~~	~~1576~~	~~*Symbiezidium barbiflorum*~~	~~Sensor 03~~	~~8~~	~~0~~	~~1121~~
~~Sensor 15~~	~~18~~	~~20~~	~~1637~~	~~*Symbiezidium barbiflorum*~~	~~Sensor 04~~	~~18~~	~~0~~	~~525~~
~~Sensor 16~~	~~18~~	~~20~~	~~1626~~	~~*Symbiezidium barbiflorum*~~	~~Sensor 05~~	~~18~~	~~0~~	~~615~~
~~Sensor 17~~	~~18~~	~~18~~	~~1655~~	~~*Symbiezidium barbiflorum*~~	~~Sensor 06~~	~~23~~	~~0~~	~~654~~

~~Sensor 18~~	~~18~~	~~17~~	~~1618~~	~~*Symbiezidium barbiflorum*~~
~~Sensor 19~~	~~23~~	~~22~~	~~1598~~	~~*Symbiezidium barbiflorum*~~
~~Sensor 20~~	~~23~~			~~*Symbiezidium barbiflorum*~~
~~Sensor 21~~	~~23~~	~~22~~	~~1484~~	~~*Symbiezidium barbiflorum*~~
~~Sensor 22~~	~~23~~	~~22~~	~~1592~~	~~*Symbiezidium barbiflorum*~~
~~Sensor 23~~	~~23~~	~~29~~	~~1653~~	~~*Symbiezidium barbiflorum*~~
~~Sensor 24~~	~~23~~	~~17~~	~~1654~~	~~*Symbiezidium barbiflorum*~~

~~Sensor 07~~	~~23~~	~~0~~	~~767~~

Table S2: Water content range measured during the calibration in the laboratory for the different replicates of the four bryophyte species. Listed are the minimum and maximum water content values (WC) measured at full water saturation ($\mathrm{WC}_{\mathrm{max}}$) and in the end of drying when weight stability was reached over more than 5 minutes ($\mathrm{WC}_{\mathrm{min}}$). Data shown for each replicate (1–4) and the species average (all).

Species	Replicate sample	$\mathrm{WC}_{\mathrm{min}}$	$\mathrm{WC}_{\mathrm{max}}$
Leucobryum martianum	1	32	1487
Leucobryum martianum	2	10	931
Leucobryum martianum	3	10	1241
Leucobryum martianum	4	7	1834
Sematophyllum subsimplex	1	14	614
Sematophyllum subsimplex	2	14	698
Sematophyllum subsimplex	3	14	468
Sematophyllum subsimplex	4	14	459
Sematophyllum subsimplex	5	7	1576
Symbiezidium barbiflorum	1	15	1657
Symbiezidium barbiflorum	2	15	1982
Symbiezidium barbiflorum	3	15	1581
Symbiezidium barbiflorum	4	22	1412
Octoblepharum cocuiense	1	23	742
Octoblepharum cocuiense	2	16	870
Octoblepharum cocuiense	3	6	2342
Leucobryum martianum	all	15	1373
Sematophyllum subsimplex	all	13	763
Symbiezidium barbiflorum	all	16	1658
Octoblepharum cocuiense	all	15	1318

~~Table S3: Electrical conductivity data and the resulting range of water content data. Besides the original minimum and maximum values of electrical conductivity (Min_total, Max_total), the ranges after subtraction of 0.1, 1 and 5% of the data from the upper and lower end are shown (Min_0.1, Min_1, Min_5, Max_5, Max_1, Max_0.1). Calculations are based on the field measured electrical conductivity data at 5-minute intervals, given for the 24 sensors. The percentiles chosen: 0.1 and 99.9 are marked in red.~~

-	-	-	~~**Percentiles of the electrical conductivity (EC) of the 5-min interval**~~							
~~**Sensor Nr**~~	~~**Species**~~	~~**Division**~~	~~**Min_total**~~	~~**Min_0.1**~~	~~**Min_1**~~	~~**Min_5**~~	~~**Max_5**~~	~~**Max_1**~~	~~**Max_0.1**~~	~~**Max_total**~~
-	-	-	~~**[mV]**~~	~~**[mV]**~~	~~**[mV]**~~	~~**[mV]**~~	~~**[mV]**~~	~~**[mV]**~~	~~**[mV]**~~	~~**[mV]**~~
~~1~~	~~*Sematophyllum subsimplex*~~	~~Moss~~	~~**24**~~	~~**27**~~	~~32~~	~~39~~	~~408~~	~~783~~	~~**1223**~~	~~**1935**~~
~~2~~	~~*Sematophyllum subsimplex*~~	~~Moss~~	~~**23**~~	~~**27**~~	~~33~~	~~41~~	~~303~~	~~450~~	~~**670**~~	~~**1392**~~
~~3~~	~~*Sematophyllum subsimplex*~~	~~Moss~~	~~**35**~~	~~**36**~~	~~38~~	~~40~~	~~372~~	~~759~~	~~**1100**~~	~~**1615**~~
~~4~~	~~*Leucobryum martianum*~~	~~Moss~~	~~**35**~~	~~**38**~~	~~39~~	~~41~~	~~72~~	~~174~~	~~**391**~~	~~**1039**~~
~~5~~	~~*Sematophyllum subsimplex*~~	~~Moss~~	~~**24**~~	~~**37**~~	~~38~~	~~41~~	~~352~~	~~721~~	~~**1076**~~	~~**1741**~~
~~6~~	~~*Sematophyllum subsimplex*~~	~~Moss~~	~~**5**~~	~~**6**~~	~~15~~	~~37~~	~~236~~	~~406~~	~~**542**~~	~~**965**~~
~~7~~	~~*Symbiezidium barbiflorum*~~	~~Liverwort~~	~~**14**~~	~~**16**~~	~~17~~	~~20~~	~~77~~	~~571~~	~~**1004**~~	~~**1427**~~
~~8~~	~~*Octoblepharum cocuiense*~~	~~Moss~~	~~**14**~~	~~**15**~~	~~16~~	~~19~~	~~55~~	~~66~~	~~**155**~~	~~**662**~~
~~9~~	~~*Octoblepharum cocuiense*~~	~~Moss~~	~~**12**~~	~~**15**~~	~~17~~	~~20~~	~~77~~	~~172~~	~~**356**~~	~~**787**~~
~~10~~	~~*Octoblepharum cocuiense*~~	~~Moss~~	~~**14**~~	~~**16**~~	~~18~~	~~21~~	~~103~~	~~189~~	~~**411**~~	~~**654**~~
~~11~~	~~*Symbiezidium barbiflorum*~~	~~Liverwort~~	~~**32**~~	~~**35**~~	~~37~~	~~38~~	~~86~~	~~264~~	~~**578**~~	~~**1255**~~
~~12~~	~~*Symbiezidium barbiflorum*~~	~~Liverwort~~	~~**29**~~	~~**33**~~	~~35~~	~~36~~	~~54~~	~~218~~	~~**429**~~	~~**900**~~
~~13~~	~~*Symbiezidium barbiflorum*~~	~~Liverwort~~	~~**40**~~	~~**42**~~	~~44~~	~~48~~	~~495~~	~~646~~	~~**803**~~	~~**868**~~
~~14~~	~~*Symbiezidium barbiflorum*~~	~~Liverwort~~	~~**39**~~	~~**42**~~	~~44~~	~~47~~	~~147~~	~~199~~	~~**239**~~	~~**328**~~
~~15~~	~~*Symbiezidium barbiflorum*~~	~~Liverwort~~	~~**46**~~	~~**50**~~	~~52~~	~~54~~	~~177~~	~~228~~	~~**312**~~	~~**350**~~
~~16~~	~~*Symbiezidium barbiflorum*~~	~~Liverwort~~	~~**46**~~	~~**50**~~	~~53~~	~~57~~	~~88~~	~~167~~	~~**237**~~	~~**363**~~
~~17~~	~~*Symbiezidium barbiflorum*~~	~~Liverwort~~	~~**32**~~	~~**37**~~	~~39~~	~~43~~	~~156~~	~~235~~	~~**315**~~	~~**638**~~
~~18~~	~~*Symbiezidium barbiflorum*~~	~~Liverwort~~	~~**41**~~	~~**41**~~	~~44~~	~~47~~	~~107~~	~~313~~	~~**555**~~	~~**1890**~~
~~19~~	~~*Symbiezidium barbiflorum*~~	~~Liverwort~~	~~**43**~~	~~**50**~~	~~54~~	~~60~~	~~141~~	~~190~~	~~**244**~~	~~**595**~~
~~20~~	~~*Symbiezidium barbiflorum*~~	~~Liverwort~~	-	-		-	-		-	-
~~21~~	~~*Symbiezidium barbiflorum*~~	~~Liverwort~~	~~**31**~~	~~**39**~~	~~44~~	~~48~~	~~152~~	~~285~~	~~**543**~~	~~**959**~~
~~22~~	~~*Symbiezidium barbiflorum*~~	~~Liverwort~~	~~**47**~~	~~**52**~~	~~56~~	~~61~~	~~139~~	~~206~~	~~**485**~~	~~**859**~~
~~23~~	~~*Symbiezidium barbiflorum*~~	~~Liverwort~~	~~**65**~~	~~**74**~~	~~79~~	~~84~~	~~117~~	~~136~~	~~**220**~~	~~**571**~~
~~24~~	~~*Symbiezidium barbiflorum*~~	~~Liverwort~~	~~**69**~~	~~**83**~~	~~89~~	~~94~~	~~123~~	~~198~~	~~**297**~~	~~**546**~~

Table ~~S4~~S3: Monthly mean values and standard deviations (± SD) of photosynthetically active radiation (PAR_{avg} daytime, measured at 75 m), daily maxima of photosynthetically active radiation (PAR_{max}), temperature (measured at 26 m), and relative humidity (RH, measured at 26 m). Rainfall is presented as the monthly amounts and the percentage of days with rain (measured at 81 m), and also the percentage of days when rain detection malfunctioned are listed. Fog events are given as the percentage of days. Dry season data are shaded in red, wet season data in blue and transitional periods are unshaded. Due to data gaps in the measured rain data (shown in brackets) values for 21 days of rain were also extrapolated from existing data as described in methods section (values behind data in brackets). Values were calculated from 30-minute intervals. Fog has not being recorded in the time ranges of 31.05. – 20.10.2015, 30.04. – 06.07.2016, 01.09. – 31.12.2016 due to malfunction of the device.

Month	PAR_{avg} daytime [µmol m^{-2} s^{-1}]		PAR_{max} [µmol m^{-2} s^{-1}]		Temperature [°C]		RH [%]		Rain [mm $month^{-1}$]	Rain [% days]	Defect on rain detection [% days]	Fog [% days]
	Mean	± SD	Mean	± SD	Mean	± SD	Mean	± SD				
Oct 2014	857	668	2201	509	26.0	2.8	90	11	212	58	0	55
Nov 2014	832	624	2082	423	25.6	2.9	92	11	70	57	0	53
Dec 2014	843	582	2140	346	26.3	2.7	90	11	123	42	0	42
Jan 2015	637	525	1747	735	24.5	2.4	95	8	259	71	0	71
Feb 2015	774	589	2058	600	25.4	2.6	92	10	140	64	0	46
Mar 2015	680	534	2038	575	24.7	2.1	96	7	331	87	0	77
Apr 2015	766	564	2155	463	25.3	2.5	93	10	189	80	0	40
May 2015	725	559	2103	425	27.2	n.a.	93	6	320	90	0	58
Jun 2015	804	562	2237	128	25.0	2.3	94	8	178	80	0	0*
Jul 2015	892	605	2238	188	25.7	3.0	91	11	74	65	0	0*
Aug 2015	1017	636	1722	957	27.1	3.3	83	13	(23) 32*	23	23	0*
Sep 2015	1148	687	2242	467	28.7	3.7	74	15	38	13	20	0*
Oct 2015	968	635	2072	514	28.4	3.6	78	16	55	35	3	13*
Nov 2015	887	624	1859	769	27.9	3.5	81	16	(33) 37*	30	17	23
Dec 2015	862	575	2074	304	28.1	3.0	78	14	38	26	3	6
Jan 2016	882	606	2175	270	28.2	3.4	78	16	52	48	0	13
Feb 2016	743	550	1928	679	25.9	2.6	93	10	(267) 341*	79	52	48
Mar 2016	692	545	2041	545	25.6	2.1	96	7	304	90	0	77
Apr 2016	709	564	2088	443	25.6	2.3	96	7	277	87	0	73
May 2016	817	603	2230	405	26.1	2.6	94	8	236	90	0	0*
Jun 2016	828	584	2178	261	25.6	2.8	92	10	105	57	0	0*
Jul 2016	917	629	2253	118	26.2	3.2	88	12	92	58	0	26*
Aug 2016	1016	648	2146	593	27.1	3.5	83	14	40	32	3	16
Sep 2016	947	662	2230	543	26.5	3.1	89	12	(77) 96*	50	17	0*
Oct 2016	915	641	2323	192	27.1	3.3	86	14	(1) 9*	23	23	0*
Nov 2016	911	610	2227	217	27.1	3.3	87	13	(30) 89*	20	13	0*
Dec 2016	694	553	1955	503	25.4	2.7	94	10	223	71	0	0*

(*) Gaps in the data record due to malfunction of the device.

Table ~~S5~~S4: Parameters determining the time range of photosynthesis and respiration. The ranges of values defining the lower water compensation point (WCP), the lower light compensation point (LCP_l), the temperature for optimal net photosynthesis (T_{opt}), and the upper temperature compensation point (TCP) as relevant parameters have been extracted from published studies conducted at various study sites in the tropical rain forest.

Parameter	Range of values	Reference	Study site
WCP	30–80 % DW	Wagner et al 2013	Panama, lowland rain forest, 0 m
LCP_l	3–12 µmol m^{-2} s^{-1}	Lösch et al. 1994	Zaire, lowland rain forest, 800 m
T_{opt}	24–27 °C	Wagner et al 2013	Panama, lowland rain forest, 0 m
TCP	30–36 °C	Wagner et al 2013	Panama, lowland rain forest, 0 m

Table ~~S6~~S5: Monthly mean values and standard deviations (± SD) of the photosynthetically active radiation (PAR_{avg} daytime), the daily maxima of photosynthetically active radiation (PAR_{max}), temperature, and water content of bryophytes at four height levels. Dry season data are shaded in red, wet season data in blue and transitional periods are unshaded. Values were calculated from 30-minute intervals. N.a.: data not available.

Month	PAR_{avg} daytime[µmol m^{-2} s^{-1}]								PAR_{max} [µmol m^{-2} s^{-1}]							
	1.5 m		8 m		~~18 m~~	-	23 m		1.5 m		8 m		~~18 m~~	-	23 m	
	Mean	± SD	Mean	± SD	~~Mean~~	~~± SD~~	Mean	± SD	Mean	± SD	Mean	± SD	~~Mean~~	~~± SD~~	Mean	± SD
Oct 2014	4	8	30	31	~~55~~	~~63~~	88	90	75	105	285	231	~~465~~	~~369~~	624	286
Nov 2014	4	11	23	32	~~27~~	~~18~~	24	37	142	131	396	321	~~188~~	~~185~~	378	275
Dec 2014	6	18	31	50	~~52~~	~~28~~	25	33	236	172	435	228	~~201~~	~~173~~	346	235
Jan 2015	3	8	22	28	~~46~~	~~24~~	20	27	155	96	341	219	~~189~~	~~167~~	341	246
Feb 2015	2	3	31	21	~~52~~	~~25~~	16	17	46	33	173	183	~~187~~	~~139~~	234	244
Mar 2015	3	4	43	35	~~42~~	~~25~~	16	15	45	55	292	159	~~159~~	~~125~~	128	117
Apr 2015	6	20	80	105	~~48~~	~~41~~	16	18	346	310	480	231	~~351~~	~~232~~	241	231
May 2015	6	32	66	71	~~52~~	~~52~~	16	17	634	428	282	236	~~460~~	~~207~~	146	137
Jun 2015	2	3	73	64	~~55~~	~~55~~	18	20	42	51	214	125	~~404~~	~~139~~	177	141
Jul 2015	3	12	54	73	~~52~~	~~59~~	15	18	168	178	727	301	~~435~~	~~169~~	152	144
Aug 2015	13	56	66	115	~~52~~	~~71~~	24	23	601	414	746	193	~~521~~	~~161~~	227	170
Sep 2015	9	21	28	47	~~53~~	~~61~~	65	66	248	204	403	224	~~410~~	~~164~~	492	229
Oct 2015	3	4	15	15	~~32~~	~~28~~	44	30	53	47	128	99	~~226~~	~~147~~	221	157
Nov 2015	4	7	16	25	~~27~~	~~21~~	61	64	82	95	315	151	~~139~~	~~98~~	475	208
Dec 2015	5	11	22	35	~~29~~	~~19~~	88	103	112	116	308	171	~~145~~	~~113~~	645	250
Jan 2016	4	7	16	21	~~33~~	~~24~~	88	103	72	91	177	143	~~165~~	~~115~~	692	294
Feb 2016	3	4	13	11	~~30~~	~~26~~	57	46	46	54	79	76	~~167~~	~~159~~	388	237
Mar 2016	3	7	28	15	~~28~~	~~27~~	37	33	102	125	107	80	~~227~~	~~180~~	268	215
Apr 2016	5	15	27	19	~~29~~	~~46~~	38	31	192	199	59	27	~~481~~	~~208~~	270	203
May 2016	3	7	n.a.	n.a.	~~34~~	~~50~~	45	41	114	109	n.a.	n.a.	~~339~~	~~176~~	286	209
Jun 2016	2	2	n.a.	n.a.	~~28~~	~~41~~	58	68	25	34	n.a.	n.a.	~~301~~	~~129~~	416	199
Jul 2016	2	4	n.a.	n.a.	~~42~~	~~64~~	72	86	30	44	n.a.	n.a.	~~386~~	~~139~~	527	204
Aug 2016	9	34	31	52	~~46~~	~~74~~	71	94	319	216	340	241	~~477~~	~~130~~	614	256
Sep 2016	3	7	13	24	~~44~~	~~63~~	55	69	102	84	250	137	~~387~~	~~166~~	508	244
Oct 2016	2	3	7	9	~~43~~	~~61~~	47	54	35	28	106	71	~~428~~	~~241~~	421	219
Nov 2016	3	5	9	13	~~33~~	~~30~~	73	85	59	51	172	114	~~216~~	~~185~~	606	251
Dec 2016	4	12	24	38	~~24~~	~~19~~	52	56	156	131	361	282	~~117~~	~~96~~	457	274

Continuation of Table ~~S6~~S5

	Temperature [°C]								Water content [% DW]									
Month	1.5 m		8 m		~~18 m~~		23 m		1.5 m Moss		8 m Moss		~~8 m Liverwort~~		~~18 m Liverwort~~		23 m Liverwort	
	Mean	± SD	Mean	± SD	~~Mean~~	~~± SD~~	Mean	± SD	Mean	± SD	Mean	± SD	~~Mean~~	~~± SD~~	~~Mean~~	~~± SD~~	Mean	± SD
Oct 14	25.0	1.3	25.2	1.6	~~25.6~~	~~2.1~~	26.3	2.9	115~~186~~	107~~150~~	110~~215~~	111~~120~~	~~59~~	~~17~~	~~201~~	~~112~~	42~~350~~	20~~17~~
Nov 14	25.3	1.2	25.7	1.4	~~25.9~~	~~1.8~~	26.2	2.3	38~~57~~	30~~34~~	53~~150~~	16~~26~~	~~56~~	~~7~~	~~182~~	~~115~~	42~~342~~	20~~17~~
Dec 14	25.4	1.1	25.8	1.3	~~26.1~~	~~1.6~~	26.6	2.1	49~~70~~	48~~64~~	56~~157~~	20~~32~~	~~56~~	~~8~~	~~186~~	~~107~~	35~~268~~	7~~83~~
Jan 15	24.2	1.1	24.3	1.3	~~24.5~~	~~1.7~~	24.6	1.8	129~~151~~	113~~131~~	76~~189~~	32~~44~~	~~60~~	~~10~~	~~183~~	~~88~~	39~~302~~	12~~10~~
Feb 15	24.5	1.0	24.5	1.1	~~25.0~~	~~2.0~~	25.0	1.8	87~~124~~	67~~92~~	69~~181~~	33~~43~~	~~59~~	~~7~~	~~170~~	~~53~~	38~~335~~	8~~92~~
Mar 15	24.4	0.9	24.3	0.9	~~24.6~~	~~1.6~~	24.5	1.3	106~~153~~	65~~97~~	102~~212~~	64~~75~~	~~68~~	~~10~~	~~217~~	~~79~~	38~~352~~	6~~76~~
Apr 15	24.6	0.9	24.7	1.1	~~25.0~~	~~1.8~~	24.9	1.8	79~~107~~	65~~88~~	73~~169~~	31~~32~~	~~61~~	~~9~~	~~229~~	~~96~~	39~~294~~	8~~75~~
May 15	24.6	0.9	24.5	0.9	~~24.8~~	~~1.7~~	24.8	1.7	130~~159~~	90~~122~~	103~~230~~	58~~72~~	~~59~~	~~8~~	~~192~~	~~63~~	39~~290~~	8~~75~~
Jun 15	24.5	0.9	24.5	1.0	~~25.0~~	~~1.9~~	25.0	1.9							~~199~~	~~30~~	~~303~~	~~77~~
Jul 15	24.5	1.1	25.0	1.5	~~25.5~~	~~2.4~~	25.5	2.5	37~~58~~	24~~31~~	103~~160~~	45~~43~~	~~53~~	~~10~~	~~200~~	~~37~~	49~~315~~	23~~14~~
Aug 15	25.4	1.2	26.3	2.0	~~26.9~~	~~2.7~~	27.0	2.8	20~~39~~	10~~14~~	67~~151~~	17~~36~~	~~46~~	~~9~~	~~181~~	~~49~~	42~~271~~	21~~98~~
Sep 15	27.0	1.7	27.8	2.2	~~28.5~~	~~3.2~~	29.0	3.4	13~~31~~	17~~25~~	60~~132~~	15~~36~~	~~41~~	~~10~~	~~154~~	~~44~~	36~~214~~	18~~11~~
Oct 15	27.2	1.8	28.0	2.2	~~28.4~~	~~3.1~~	29.4	3.2	13~~30~~	16~~19~~	36~~196~~	21~~74~~	~~42~~	~~10~~	~~154~~	~~48~~	43~~242~~	52~~13~~
Nov 15	27.2	1.9	27.6	2.3	~~28.1~~	~~3.1~~	29.2	3.6	16~~37~~	14~~21~~	51~~197~~	30~~74~~	~~45~~	~~19~~	~~157~~	~~43~~	37~~249~~	32~~11~~
Dec 15	27.3	1.6	27.9	2.0	~~28.2~~	~~2.6~~	29.4	3.4	15~~35~~	11~~15~~	48~~187~~	24~~72~~	~~43~~	~~15~~	~~156~~	~~43~~	35~~241~~	18~~10~~
Jan 16	27.4	1.8	28.0	2.2	~~28.4~~	~~3.0~~	29.4	3.8	16~~37~~	14~~21~~	51~~133~~	31~~51~~	~~42~~	~~16~~	~~151~~	~~47~~	37~~249~~	16~~10~~
Feb 16	25.2	1.0	25.4	1.2	~~25.8~~	~~2.1~~	26.2	2.5	80~~126~~	93~~120~~	99~~164~~	80~~83~~	~~67~~	~~39~~	~~190~~	~~52~~	43~~296~~	16~~11~~
Mar 16	25.2	0.9	25.1	0.9	~~25.4~~	~~1.6~~	25.6	1.8	74~~122~~	68~~96~~	91~~151~~	49~~59~~	~~71~~	~~30~~	~~187~~	~~50~~	41~~233~~	13~~73~~
Apr 16	25.2	1.0	25.2	1.1	~~25.5~~	~~1.7~~	25.7	2.0	63~~106~~	45~~64~~	131~~188~~	85~~83~~	~~90~~	~~47~~			43~~240~~	14~~85~~
May 16	25.3	1.0	25.3	1.2	~~25.8~~	~~1.9~~	26.1	2.3	42~~75~~	33~~47~~	75~~158~~	39~~59~~	~~52~~	~~26~~			44~~221~~	16~~74~~
Jun 16	24.6	1.1	24.6	1.3	~~25.3~~	~~2.2~~	25.8	2.8	31~~58~~	18~~25~~	61~~159~~	30~~62~~					45~~298~~	13~~85~~
Jul 16	24.8	1.2	25.3	1.7	~~25.9~~	~~2.5~~	26.7	3.4	24~~50~~	22~~28~~	52~~165~~	21~~64~~					53~~317~~	36~~13~~
Aug 16	25.7	1.8	26.3	2.4	~~26.9~~	~~3.0~~	28.0	4.1	22~~36~~	28~~31~~	59~~143~~	99~~75~~					59~~259~~	130~~8~~
Sep 16	25.5	1.3	25.9	1.7	~~26.4~~	~~2.6~~	27.1	3.3	28~~40~~	40~~38~~	52~~155~~	39~~73~~					67	111
Oct 16	26.2	1.6	26.8	1.9	~~27.3~~	~~2.9~~	28.0	3.4	17~~31~~	9~~9~~	45	18					43	38
Nov 16	25.9	1.7	26.5	2.1	~~27.1~~	~~2.8~~	28.0	3.4	18~~45~~	20~~32~~	49~~157~~	49~~118~~	~~153~~	~~242~~	~~285~~	~~215~~	44~~256~~	37~~95~~
Dec 16	25.4	1.3	25.0	1.7	~~25.3~~	~~2.1~~	25.6	2.5	~~79~~	~~67~~	~~234~~	~~134~~	~~359~~	~~372~~	~~459~~	~~319~~	~~386~~	~~167~~

Table S6: Mean values and standard deviations (± SD) of the daily maxima of photosynthetically active radiation (PAR_{max}) for each height level shown for 2015 and 2016, considering that 2015 was an El Niño year (additional information to Table 1).

	PAR_{max} [µmol m^{-2} s^{-1}]			
Height	**2015**		**2016**	
	Mean	**± SD**	**Mean**	**± SD**
above canopy	1766	415	1842	364
23 m	125	123	226	140
8 m	186	195	68	90
1.5 m	49	89	29	45

Table S7: Mean values and standard deviations (± SD) of the daily maxima of photosynthetically active radiation (PAR_{max}) for each height level shown for the different seasons (additional information to Table 2).

Height [m]	**PAR_{max} [µmol m^{-2} s^{-1}]** Mean	 ± SD
Wet season		
above-canopy	1687	431
23 m	245	82
8 m	210	151
1.5 m	191	206
Transitional season Wet-Dry		
above-canopy	1855	233
23 m	318	183
8 m	471	363
1.5 m	66	68
Dry season		
above-canopy	1924	370
23 m	457	147
8 m	314	184
1.5 m	172	177
Transitional season Dry-Wet		
above-canopy	1691	407
23 m	496	165
8 m	324	95
1.5 m	146	61