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

Dear Professor Bahn,

we would like to thank you and the reviewers for the initial manuscript evaluation and the comments, which helped to improve our manuscript. We appreciate the opportunity to revise our manuscript to address the constructive comments and suggestions from the reviewers. Below we respond with a point-by-point explanation to the comments from each 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.

Maaike Bader as Referee submitted the comments RC1 and RC3

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.

Maaike Bader RC1

Received and published: 10 February 2019

General Referee comment:

Dear authors,

The manuscript "Microclimatic and ecophysiological conditions experienced by epiphytic bryophytes in an Amazonian rain forest" presents interesting data about the microclimate experienced by epiphytic bryophytes in a tropical rainforest, as well as unique measurements of the time these organisms stay wet. Such data is indeed very valuable for understanding the distribution and ecophysiological behavior of such mosses and liverworts. The data are well-presented graphically at different time scales, showing seasonal and diel patterns. There are some issues about the presentation of the interpretation that need addressing though, as explained below.

General author response:

We would like to thank Maaike Bader for the very constructive review and the helpful comments, which helped us to identify the critical aspects and to improve our manuscript.

Referee comment 1:

It is clear that is a great effort to measure such data in a rain forest environment and the difficulty of canopy access. Because of this, and because of the absence of comparable data, the lack of replication (all samples were located close together on one stem or branch section per height on the tree) can be 'forgiven', but it should be mentioned and evaluated in the text!

Author comment 1:

We fully agree that it would be preferable to install sensors on several different trees in order to have fully independent true replicates. However, as you stated correctly, it is a great effort to install and run microclimate measurements in such a rain forest environment. Thus, we installed several sensors at each height in order to cover the variability at least to some extent. We added some more information about the incomplete replications in the methods section to explain the limitation of the measurement setup.

Author changes in the text 1:

P 7 L12: "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. "

Referee comment 2:

I am also very aware of the almost complete lack of basic ecophysiological data on gas exchange in tropical lowland bryophytes, data being available for only 6 species, presented in Wagner et al 2013. However, I do not think that this justifies using data from tropical montane forest species, especially not for temperature responses, which differ along elevation (as shown in the cited paper by Wagner et al), but also not for water content responses, because montane species experience very different water regimes and are likely to employ different strategies concerning the preservation and use of their water contents – that is to say, the 'community weighted mean' of the strategies is likely to be different. I do think that it is a valuable exercise to estimate activity times for net photosynthesis and net respiration, but I think the lack of physiological data to base this estimation on needs to be dealt with differently. Some of the cited parameters (which are from montane species) are so unlikely (like a lower activity level for water content of 225%...) or uncertain (note that in Wagner et al it is explicitly mentioned that the absolute carbon exchange values should be treated with caution because of uncertainty in the absolute carbon exchange rates measured. This is not a problem for the optimum ranges (T and WC), but it is a problem for the compensation points, to which your calculation is highly sensitive. I would recommend to use only the lowland data and to use these data more loosely, using them combined with your common sense to estimate (or select) likely parameter values and presenting only theoretical calculations like " if we assume that the LCP is 6 µmol/m2/s, the total A and Rd times would be x and x% of the time, whereas a LCP of 1 µmol/m2/s would allow net A x% of the time". This is not fundamentally different from your current presentation, but you could avoid having to present estimations of 0-100%, which are not very helpful, and it would acknowledge the fact that gas exchange data for lowland species are simply not sufficiently available to really allow the type of estimates you would like to make at this point.

Author comment 2:

Thank you very much for this helpful comment! It is correct that the data collected at montane rainforest sites are not suited for a comparison and thus we now refrain to the lowland forest data (location BT) given in Wagner et al. (2013).

For the light compensation point (LCP) we include another reference for bryophytes in lowland bamboo forests with values of 3-12 µmol s^2s^{-1} for the LCP (Lösch et al., 1994).

For the current manuscript we omitted the information on saturation points, as we found that the current data are not well-suited for an inclusion of these data.

Author changes in the text 2:

All tables, figures, and the values in the text have been adapted according to the revised calculations and the wording is now more careful according to the referee suggestions.

Referee comment 3:

Considering my previous point this one may be obsolete now, but it is not clear how the parameters in table 3 and S2 or those presented in L17-18 P9 were selected from Wagner et al 2013. Also, a 'water content compensation point' was not presented in Wagner et al although the paper is cited for it.

Author comment 3:

As described above, we now only consider the BT site located at sea level (see Tab. 3 and Tab S3). Accordingly, we cite the optimum temperature range with 24°C limiting the lower and 27°C limiting the upper end of the range as reported in Tab. 3 of Wagner et al. (2013).

The lower and upper temperature compensation points "TCP" of 30.0 and 36 °C were reported in Wagner et al. 2013 Tab. 3 as the temperatures when "$T_{NP=DR}$" for the site BT at sea level.

Data on the water compensation point were extracted from Fig. 1 in Wagner et al. 2013.

Author changes in the text 3:

The text and tables (Tab 3, Tab S3) were adapted accordingly.

Referee comment 4:

Also, a lot of the statements about ‘tropical bryophytes’ are supported by literature from montane forests, and a lot of the statements about ‘epiphytic cryptogams’ are based on literature on lichens. This is not wrong but it is a bit deceiving. There would be nothing wrong with emphasizing, not only at the end of the discussion but right up front, that very little data is available for tropical lowland bryophytes and that therefore you need to rely on quite a bit of rough guessing and extrapolation of results from other areas and other organisms. As long as you make clear what your limitations are, they can be dealt with.

- So: make clear what literature is about lichens and what is about mosses – although these organisms have eco-physiological similarities, they are not the same in all respects! For example, enthanolic fermentation and bioaerosols have been observed for lichens but not for bryophytes, or am I wrong?

- And: be very careful, and be explicit about it, with using parameters and process knowledge based on montane forests and on lichens.

Author comment 4:

Thank you for your comment; we are aware that lichens and bryophytes do not behave identically in all respects, although there are quite some similarities. Thus, in the revised version we stress whenever we use information on lichens. When comparing our results with those from other studies, we specify the rainforest habitat and organism group.

Author changes in the text 4:

P 13 L2: “Furthermore, high nighttime temperatures cause increased carbon losses due to high respiration rates, as previously shown for lichens (Lange et al., 1998, 2000).”

P 19 L 33: “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).“

Referee comment 5:

Water content can hardly be called ‘ecophysiological conditions’, I would recommend removing this term from the title. To make sure that the innovative data on water content are in the title, you could consider changing it to “Microclimatic conditions and water content fluctuations experienced by epiphytic bryophytes in an Amazonian rain forest”

Author comment 5:

We agree with your comment on the ‘ecophysiological conditions’. Your recommended change of the title is a good solution and thus we adapted it.

Author changes in the text 5:

Title: “Microclimatic conditions and water content fluctuations experienced by epiphytic bryophytes in an Amazonian rain forest”

Referee comment 6:

The statement “Our data suggest that water contents are decisive for overall physiological activity, and light intensities determine whether net photosynthesis or dark respiration occurs, whereas temperature variations are only of minor relevance in this environment.” In the abstract, and the statement that ‘water content has turned out to be key’ is not justified by your results. It is probably the case, but this is not suggested by your data – it could not be and was not addressed in your study, as realistic data about gas exchange is missing.

Author comment 6:

Thank you for your comment. Yes, we indeed do not have CO_2 gas exchange data in this study. Nevertheless, we think that already the microclimate data by themselves and the calculations on potential activity patterns support our statement that water contents are highly relevant whereas temperatures are of minor importance for physiological activity. Nevertheless, we try to clarify these issues in the revised version of the manuscript.

Author change in the text 6:

Changes were made in the abstract and the discussion sections to clarify these issues.

P 2 L 24: “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. These data may be used as a starting point to investigate the role of bryophytes in various biosphere-atmosphere exchange processes, such as measurements of CO_2 gas exchange, and could be a tool to understand the functioning of the epiphytic community in greater detail.”

Referee comment 7:

There is a lot of information in the methods section that is superfluous or irrelevant, whereas other information is missing. Superfluous/irrelevant: P4 L 24-26, 29-32; P5 L13-15; Equations 5-8; P6 L20 brand name of styrodur.

Author comment 7:

We agree to delete some information on the study site (P6 L 23-24) and on the neighboring forest types (P6 L 27-30).The styrodur brand (P9 L25) and the equations 5-8 (P 10 L 18ff) have been deleted due to overall revision of the calibration process.

Referee comment 8:

There is basically no information about the statistical analyses other than in what software they were performed… Please explain what was tested, what were your units of replications, etc.

Author comment 8:

We agree with the comment, there was not enough information regarding statistical analyses. However, with the new calibration procedure and the situation of statistical replicates (e.g., light n=2, temperature n=2, above canopy light n=1, above canopy temperature n=1, above canopy RH n=1), we decided to delete the statistical tests and shortened this section considerably (P 14 L6-9). Thus, we also renamed this section, being now called "Data analysis".

Referee comment 9:

I am a bit afraid that you have used days as replications to compare climatic variables between years – is 26.6° really different from 26.4° C, or even 25.8° is different from 25.8° (Table 1)?? With enough (pseudo)replication any tiny difference can become 'significant', but that does not make it real…

Author comment 9:

Thank you very much for that good advice. We thought about this test again and decided to delete it, as the values indeed are not independent.

Referee comment 10:

Please present your experimental design (what species, what positions, justification for the pseudoreplication), preferably early in the methods section.

Author comment 10:

More details (that were previously in the Supplement) are now included in the text, section "2.2 Microclimatic conditions within epiphytic habitat". Furthermore we added the new Figures S2 and S3 to the Supplement showing the distribution of all the sensors along the vertical gradient and the morphological characteristics of the bryophyte species.

Author change in the text 10:

P7 L16-26: "Generally, the WC sensors were placed in four different bryophyte communities being heterogeneously distributed along the four 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 sensors) and *Symbiezidium barbiflorum* (3 sensors), and at 18 and 23 m in *Symbiezidium barbiflorum* (6 sensors at each height level; Fig. S2, Fig. S3). The temperature sensors were installed in the same communities at each height, 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 were observed (Tab. S1). The sensors were installed with the following orientations: at 1.5 and 8 m vertically along the trunk, at 18 m at the upper side of a slightly sloped branch, and at 23 m at the upper side of a vertical branch. Thus, also the orientation at the stem may influence the WC of the bryophyte communities, not only the species and the canopy structure."

Supplement: Figure S2 and Figure S3 (see below) were added to the supplement.

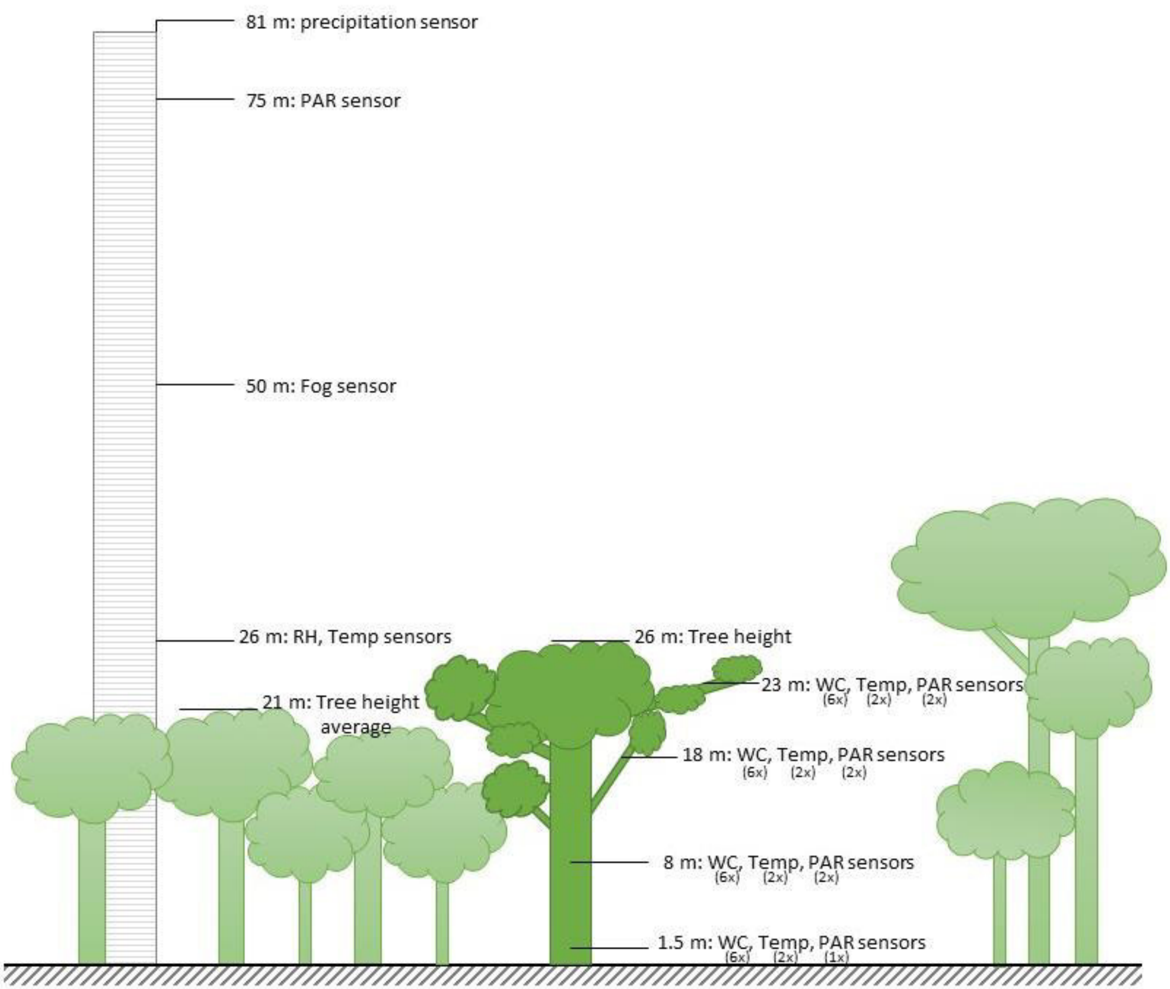

Figure S2: Schematic overview on the sensors installed at different height levels below, within, and above the canopy. The parameters water content (WC) and temperature (Temp) were measured within the bryophyte samples, the light sensors (PAR) were installed directly on top of the thalli. The average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

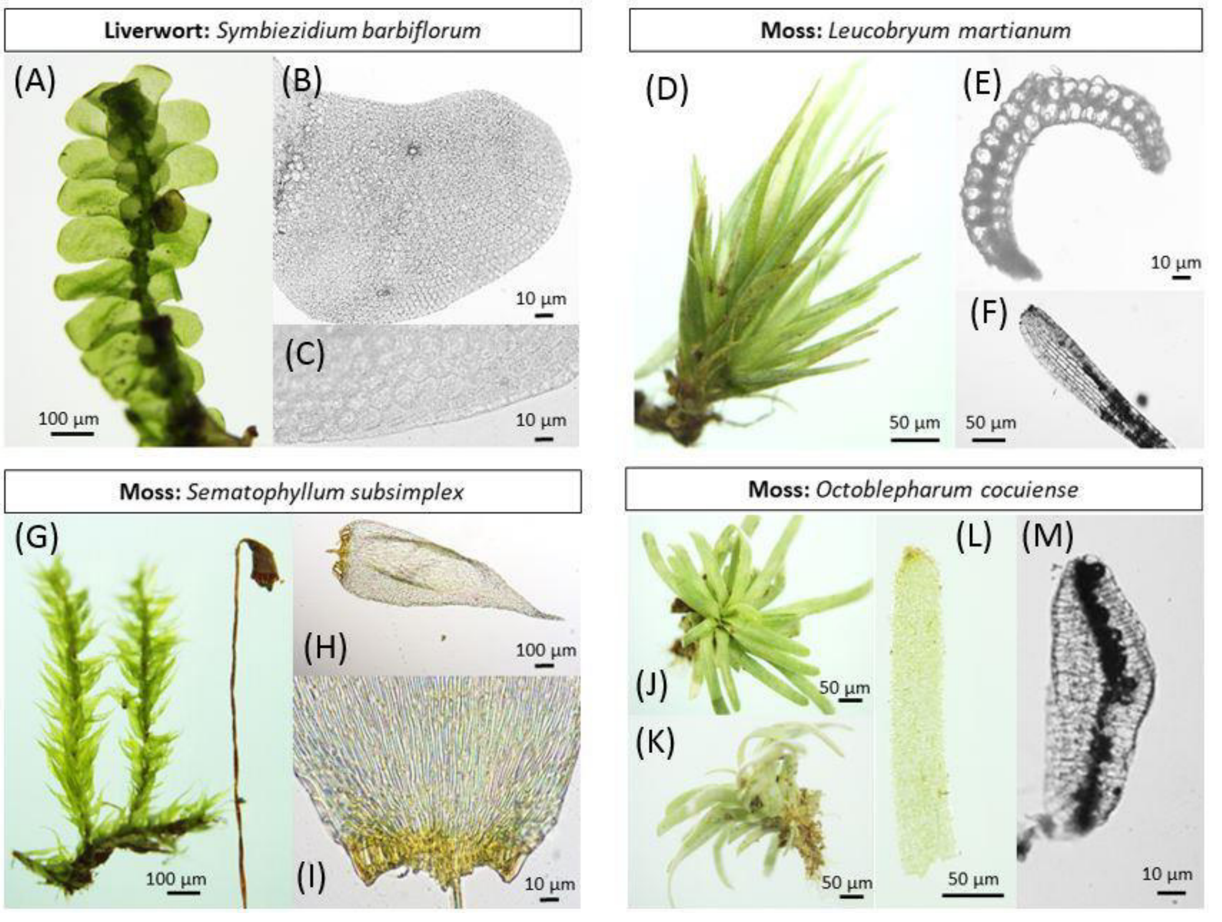

Figure S3: The four bryophyte species being used for installation of the sensors of the microclimate station. (A, D, G, J, K) overview, (B, H, L) leaf, (C, F I) cell form, and (E, M) cross section of a leaf.

Referee comment 11:

It was not clear whether you used the 5-minute resolution data for calculating the times for A and Rd, or whether you only used the half-hour smoothed data. The smoothed data are fine for studying seasonal differences, but for the activity times and for quantifying the frequency of sun flecks (which would be interesting to do!) I would recommend using the 5-minute data.

Author comment 11:

For a calculation of A and Rd, the 5-minute data were used, as written in Table 3. We additionally provide this information in the methods section on P11 L31.

Author change in the text 11:

P11 L31:“Thus, for all calculations the 30-minute averages have been considered, except for the estimates of physiological activity. “

Referee comment 12:

You mention that the conductivity showed 'short-time oscillations' - could these be explained physically? Were they regular fluctuations or just general instability?

Author comment 12:

The oscillations of the sensors represent a general instability of the system, as the measured values oscillated around the actual values. Accordingly, the 5-minute data set was only used for an estimation of the physiological activity, as here the information on short-term events (as e.g. light flecks) is needed. For all other calculations, the 30-minute averages were used.

Author changes in the text 12:

P11 L30: "The measured electrical conductivity values showed short-time oscillations, which could be removed with a 30-minute smoothing algorithm (Fig. S4). *Thus, for all calculations the 30-minute averages have been considered, except for the estimates of physiological activity*."

Referee comment 13:

Limitations should not only be acknowledged for the availability of gas-exchange parameters, but also, and early in the manuscript, for the measurements themselves. In particular, the quality of the WC calibration curves could be a problem. The calibration graphs show that there is indeed great variation between samples and between measurements, and that the models do not reflect the water contents very well even for the calibration data. As an example for the variability, the curves show that a conductivity of 800 mV (why is conductivity expressed in mV?? Should this not be in Ohm?) in Symbiezidium could be caused by a water content anywhere between 300 and 1700 %. What is the effect of this uncertainty on your results? For Octoblepharum the model underestimates the WC over much of the range (can this explain the low WC at 8 m?). For Sematophyllum the maximum conductivity measured in the field greatly surpasses the maximum values measured during calibration, which will, by the looks of it, results in a very high estimated water content even with the exponential correction. Why are these models not drawn for the whole range of measured conductivities? For example, the quadratic function for Leucobryum would mean that a very high conductivity, like the 1000 observed in the field, would indicate a lower WC than intermediate values. If you do not draw the whole curve, this potential artifact cannot be evaluated well.

Author comment 13:

After major considerations, we decided to thoroughly change the calibration routine.

Thus, also based on your reviewer comment 3, we decided to test and use an alternative approach for the calibration of the water content. For this, the maximum and minimum values of electrical conductivity reached in the field were assume that they are reached at the maximum and minimum water contents reached by the samples, whereas the amplitude of the water contents was determined based on the laboratory measurements. In the new approach we assume, that the maximum electrical conductivity in the field is achieved at the maximum water content, as determined in the laboratory.

Author change in the text 13:

P11 L4: "A calibration was conducted for 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. 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):

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

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

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 of the WCs reached during the laboratory measurements. We assume, that the maximum electrical conductivity achieved in the field equals the maximum WC achieved in the laboratory due to water saturation of the samples during the laboratory measurement. Minimum electrical conductivity values reached in the field were assumed to correspond to air-dry samples, as we are confident that the samples dried out at least once during the dry season of the year. Accordingly, the water content (WC) was calculated as follows:

$$WC\ [\%\ DW] = \frac{(EC_i - EC_{min})}{(EC_{max} - EC_{\min})} * (WC_{max} - WC_{min}), \quad (4)$$

with EC_i as electrical conductivity, EC_{min} as minimum electrical conductivity, EC_{max} as maximum electrical conductivity in the field, WC_{max} as the maximum WC in the laboratory, and WC_{min} as the minimum WC in the laboratory.

Referee comment 14:

Also, the observation that water saturation was never reached at the 3 higher levels seems to suggest that something was wrong either with your WC measurements or the literature parameters used… BUT, this statement (P13, L24) cannot be true based on your data, because *Symbiezidium* is present only in these three higher levels, and in the calibration curves you show that observed values go up to 1500% WC, which is well above the WSPs cited…

Author comment 14:

You are right, according to the original calibration the WSP of 349 % WC was almost never reached in the canopy (at 23, 18, and 8 m), whereas it was reached during 22% of the time at 1.5 m height. As described above, the original calibration has been replaced and we also restrict the calculations to the compensation points, which are more relevant than the saturation points in the current context.

Referee comment 15:

It was unclear to me what "upper three height levels the bryophyte taxa could not be securely determined. Thus, the bryophyte taxon with the highest abundance in the canopy communities, i.e., the liverwort *Symbiezidium barbiflorum* was used" means exactly. Did you install sensors only in this species, or did you do the calibration curve only for this species and then use if for all the different (unidentified) species sampled at the higher height levels? This should be made clearer. I could imagine that you installed sensors in other liverworts looking similar to Symbiezidium and then assumed that the relationship between electrical conductivity and water content should not be more different between species than within species, due to the similar life form. This seems a reasonable assumption, but should be made explicit, and in table S1b the species should not be named if you do not know the real name. Indicating if it was a moss or a liverwort, or the family it belongs to, would be useful though!

Author comment 15:

The sensors were installed in bryophytes morphologically similar to *Symbiezidium barbiflorum*. However, as the sensors were installed by a climber, it could not be completely reassured that always the same species was used. Nevertheless, we know that *Symbiezidium barbiflorum* was the most dominant species in the canopy of this tree, and from all the information we have for each sensor, the identification of these samples should be correct. Furthermore, we clarified that bryophyte communities have been investigated and not single species, as in most cases a community of different species grows together. This was corrected accordingly in the text.

Author change in the text 15:

P7 L8: "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.."

Referee comment 16:

The use of different species at the different heights is a problem that also needs to be discussed earlier and more prominently and included in the analysis. It reads all through the manuscript as though differences in water content between height zones were caused by microclimatic differences, but of course a Leucobryum (cushion moss with specialized water-holding cells) is going to have very different water content dynamics that a *Symbiziedium* (prostrate leafy liverwort), even under the same environmental conditions. This is also obvious from your own data in the calibration curves, the points for Leucobryum being much closer together, indicating that the drying was much slower than e.g. for *Symbiezidium*. For Oc*t*oblepharum the two (! Looks like they were only two though you write they were three) samples dried at quite different speeds, it looks like the slow sample was denser and thus had higher conductivity at similar water contents. At the moment, the whole manuscript reads a bit as though you consider all cryptogams are expected to respond more or less the same, but we know that there are big differences between species, in particular in terms of water-content dynamics as well as the responses to this water content. Although you do mention this briefly, I think it deserves a few more words at least.

Author comment 16:

Indeed, we mixed up the replicate numbers in the Supplement Figure S3, however, this information is obsolete, due to recalculations.

Regarding the behavior of different species during the drying process, this section was extended with more information.

Author change in the text 16:

P22 L3: "The high WC of the bryophyte samples in the canopy might be partly explained by the different water holding capacity of different bryophyte species (Lakatos et al., 2006; Romero et al., 2006; Williams and Flanagan, 1996)."

P22 L24: 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 long-term adaptation of the metabolic properties, the performance of species under differing microenvironmental conditions can also be modulated by acclimation processes (intraspecific variability), as, e.g., shown for bryophytes and lichens (Cornelissen et al., 2007; Pardow et al., 2010). "

Referee comment 17:

It would be really cool if you could detect a dew signal in the WC data, did you look for this? Mention this in the discussion to but the dew remarks into the context of your data.

Author comment 17:

This indeed is a relevant aspect, and we also considered if we could calculate these values. However, in order to calculate them we would need the temperature below the bark. Due to the lack of this information we cannot calculate dew formation.

Referee comment 18:

It would also be cool if you could detect relationship between cryptogam activity patterns and measured trace gas emissions – this tall canopy site would be one of the few places in the world where the needed data might be available, assuming that trace gases above the canopy are also monitored?

Author comment 18:

Yes indeed, different trace gases are monitored at this study site and investigations on this are planned for the near future. This, however, is beyond the scope of the current manuscript.

Referee comment 19:

The literature cited needs to be revised! Only few bryophyte papers are cited and often they are not the correct ones (see below)! Some examples:

p. 3, lines 15-16: Zotz et al 1997 is cited a lot but refers to a montane forest, and not to nutrient cycling, as suggested on this occasion.

p.8, lines 30-31: 'at least in the environment of the central Amazon' is followed by references out of which none are from the central Amazon, most are from cloud forest…(by the way, this sentence is more or less repeated on page 12, L 29-31)

p. 9, lines 5-6: 'For tropical species, values (of WCPl) in the range 5 between ~ 30 and ~ 225 % have been determined (Romero et al., 2006; Wagner et al., 2013; Zotz et al., 1997, 2003)' Again, these references are all from montane species or do not mention WCPl values at all.

p. 6, lines 10 - 12: "Thus, the bryophyte taxon with the highest abundance in the canopy communities, i.e., the liverwort *Symbiezidium barbiflorum* was used (Gradstein and Allen, 1992; Mota de Oliveira et al., 2009; Mota de Oliveira and ter Steege, 2015; Pardow et al., 2012; Romanski et al., 2011; Sporn et al., 2010)." Of the 6 references cited here, *S. barbiflorum* is only mentioned in Gradstein and Allen (1992), the other 5 references do not cite this species at all! (one of the papers cited, Sporn et al. 2010, even deals with Asia even though S. barbiflorum does not occur there, being restricted to America…). Interestingly, Gradstein and Allen (1992) state that S. barbiflorum is a characteristic shade epiphyte of forest understory communities, not canopy communities. Not-cited more recent publications on the habitat of *S. barbiflorum*, however, show that the species also occurs in the forest canopy (Gradstein et al. 2001, Gradstein 2006, Gradstein & Ilkiu-Borges 2009, Gehrig et al. 2013). These recent papers show that S. barbiflorum is actually an ecological generalist, occurring in understory communities as well as in canopy communities. None of these non-cited papers document highest abundance of the species in canopy communities. Thus, the sentence on p. 6, lines 10-12, is rather wrong.

p. 3, line 12-13: "In 2013, 800 species of mosses and liverworts …,… have been reported for the Amazon region" (Mota de Oliveira & ter Steege 2013). The reference cited here is quite wrong, Mota de Oliveira & ter Steege did not provide this number at all, instead they took it from Gradstein et al. (2001; correctly cited by Mota de Oliveira & ter Steege) who calculated 800 species in the Amazon region in their book based on a full-scale analysis of the bryophyte flora of the Neotropics. Thus, the correct reference here is Gradstein et al. (2001) and not Mota de Oliveira & ter Steege.

Author comment 19:

Regarding P3 L 15-16, (Now P3 L7): reference was removed

Regarding P8 L30-31, (Now P12 L30): reference was changed; the repeated sentence was removed from P20 L21

Regarding P9 L5-6, (Now P 13 L5): The references of montane cloud forests (Romero et al. 2006, Zotz et al. 1997, Zotz et al. 2003) were removed. Only the information related to a research site at sea level in Wagner et al. 2013 was considered. The information for the WCP there is was extracted from figure 1. Perhaps we could obtain the exact values from you?

Regarding P6 L10-12, (Now P9 L12): Indeed, this sentence in its reported version was wrong. Initially, this sentence intended to tell that in general in lowland rainforest liverworts are more abundant in the canopy than in the understory, which was observed by Pardow et al. 2012. However, due to internal revisions and changes in the text, the sense of this sentence changed, unfortunately resulting in a wrong statement. The sentence meanwhile was . Furthermore, in the Material and Method section we mention that we talk about dominating species.

Regarding P3 L12-13, (Now P3 L20): We corrected the reference according to your advice.

Author change in the text 19:

P12 L30: "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)."

P13 L5: "For tropical species in lowlands near sea level in Panama, values in the range between ~30 and *~80 %* have been determined (Wagner et al., 2013; Table S3)."

P9 L12: deleted; equal information now provided in P7 L 8: "Thus, the organisms mentioned throughout this paper were the dominating but not solitarily living species."

P3 L20: "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).

Referee comment 20:

Data availability: does this local database assure future data maintenance and retrieval? Please provide more details.

Author comment 20:

Yes, this is a long term monitoring project and the database on the water content, temperature, and light conditions of epiphytes is uploaded to the ATTO data portal (www.attoproject.org/).The data thus are maintained, obtain a doi and can be retrieved from that site.

Referee comment 21:

General: rather than ‘mesoclimate’, ‘above-canopy climate’ would be a more intuitive name for those measurements.

Author comment 21:

We agree with your advice to rename the “mesoclimate” to “above-canopy climate”. Accordingly, this expression was changed throughout the text. Furthermore, the expression “ambient” was changed into ”above-canopy”.

Referee comment 22:

P3 L 9: instead of ‘these’ write ‘such’ (this is an example of the confusing mix of literature and statements about cryptogam communities in general (often based on soil crusts…) and on tropical lowland epiphytes.

Author comment 22:

P4 L31: We agree to substitute “these” by “such”, however, this sentence was deleted in the meanwhile.

Referee comment 23:

P3 L 21: careful, not all bryophytes are desiccation tolerant, even if they are poikilohydric

Author comment 23:

Yes, we agree on that and added the expression “most species” and “for many species”.

Author change in the text 23:

P 3 L12: “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).

Referee comment 24:

P4 L4-6: Add that most of this info is based on data from soil crusts and from temperate zones and that very little is known about biomass and functions of epiphytic cryptogam in tropical forests, especially in the lowlands.

Author comment 24:

That is right, that most of the fluxes were detected for soil communities. However, the information on VOC and aldehydes was performed on epiphytic lichens as well (Kesselmeier et al., 1999; Kuhn et al., 2000; Kuhn and Kesselmeier, 2000; Wilske and Kesselmeier, 1999).

This information was omitted in the meantime, due to reorganization of the whole section.

Referee comment 25:

P4 L 8: seasonal variation in what?

Author comment 25:

…the seasonal variation of climatic conditions.

The whole section was revised and this sentence was removed.

Referee comment 26:

P5 L2: why ‘ecophysiological’ water content? What other water content is there?

Author comment 26:

It is the “normal” water content of bryophytes, thus the word “ecophysiological” can be deleted.

Author change in the text 26:

P7 L2: “The parameters temperature and light within/on top of the bryophytes *and their water content* were measured with a microclimate station installed in September 2014 (Fig. S1).”

Referee comment 27:

P5 L3: use ‘were’ rather than ‘are being’, even if the measurements are continuing, because you are here presenting results of a specific period in the past. Same for P5 L 11: were taken (not have been taken)

Author comment 27:

We agree on that and changed the tenses accordingly.

Author change in the text 27:

P7 L3: “The parameters temperature and light within/on top of the bryophytes and their WC were measured with a microclimate station installed in September 2014 (Fig. S1).”

P7 L30: “Since the installation, automatic measurements at 5-minute intervals *were taken* with a data logger…”

Referee comment 28:

P5 L 5: instead of ‘described by’ use ‘used by’, because ‘described’ suggests that these zones were the output of a study, but it was the sampling design.

Author comment 28:

Done accordingly.

Author change in the text 28:

P7 L4: “…, corresponding to the zones 1 to 4 *used by* Mota de Oliveira and ter Steege (2015).”

Referee comment 29:

P5 L8: a cushion is a specific bryophyte life form, seeing your species the samples probably were not cushions in most cases…You could use ‘bryophyte samples’.

Author comment 29:

The information is now provided in another sentence, due to revision. Overall, we talk about bryophyte communities, now.

Author change in the text 29:

P7 L20: "The temperature sensors were installed in the same communities at each height, and the light sensors were installed adjacent to them on ~ 5 cm long sticks (Fig. S1).

Referee comment 30:

P5 L 19: what do you mean with 'fluctuations'?

Author comment 30:

With "fluctuation" we meant to describe the oscillations of the measurement. This was changed accordingly.

Author change in the text 30:

P8 L10: "The WC values were *oscillating, causing an inaccuracy corresponding to* approximately 15 % dry weight (DW)."

Referee comment 31:

P6 L17: are nutrient content and temperature species-specific?

Author comment 31:

Yes, the nutrient content is species-specific. But the temperature cannot be actively regulated by the species, thus it is not species-specific, but dependent on the environment. However, both parameters influence the measurements of electrical conductivity, hence it is recommended to include an assessment of the species-specific nutrient contents and to do a correction by temperature, to receive the most accurate values.

Referee comment 32:

P7 L1: what is the sensor weight?

Author comment 32:

During the calibration the sensor is fixed in the bryophyte sample and both are lying on the balance. Accordingly, the balance always reads and logs the total weight of 'sample plus sensor'. But as the weight of the sensor varies slightly depending on the tension of its wire, the weight of the sensor is not the same for each 'set of calibration measurements'. Thus, the weight of the dry' sample plus sensor' is recorded at the end of the measurement, as soon as weight consistence is given. Afterwards the sensor with its wire is removed from the sample and then only the weight of the sample can be recorded.

But the whole section was revised, and this sentence was removed.

Referee comment 33:

P7 L12: rather that presenting the models, which are very standard (except maybe for the exponential correction; if you want you could show the models in the appendix), a discussion about uncertainty propagation would be fitting here.

Author comment 33:

Due to recalculation of the WC the fits are omitted from the new version of the manuscript. A discussion on the inaccuracy of the measurements and the uncertainty of the resulting values is included in the material and methods section.

Author changes in the text 33:

P8 L10: "The WC values were oscillating, causing an inaccuracy corresponding to approximately 15 % dry weight (DW). Besides the specific position in the substrate, the WC also depended 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. "

P22 L21: "This variability of data, depending on the exact placement of the sensors, illustrates that calculated WCs could only be considered as approximate values"

Referee comment 34:

P8 L16: rainfall amounts would usually not be calculated by integration but by adding the rain amount (e.g. number of tipping events) per time period…

Author comment 34:

Yes, you are right, the rainfall amount should be summed up for certain time periods. However, sometimes rain detection was interrupted and data of short time gaps were missing. For these time periods, we decided to integrate the data not to underestimate the amount too much. We are aware of the fact, that these data gaps and the subsequent calculations may be a source of over- or underestimation. However, this to our knowledge, is the best way to deal with this problem. In addition, the data gaps were relatively small, thus not being a major source of error.

Referee comment 35:

P8 L26: explain 'UTC values'; and where are such times presented, and why not always use local time?

Author comment 35:

The UTC is the abbreviation of the universal coordinated time and it is used throughout this study. It allows the synchronization with other data sets. The local time (LT= UTC-4) is only used for the calculation and presentation of diurnal cycles, where it is explicitly marked. The UTC time is used for long data ranges, as monthly and seasonal data.

Author change in the text 35:

P12 L26:” 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.”

Referee comment 36:

P9 L23: This WCPl is not what you describe it to be (this would not be a compensation point), it is the point below which the WC is so low that photosynthesis cannot compensate respiration, respiration ceasing at lower WCs than photosynthesis.

Author comment 36:

Here indeed was a mistake. With the WCPl we wanted to explain the point, when net photosynthesis equals respiration, due to limited water availability. This was now changed in the text.

Author change in the text 36:

P13 L3: “The lower water compensation point (WCP) presents the minimum WC that allows positive *net photosynthesis*.”

Referee comment 37:

P9 L28: with ‘we found’ you mean ‘we assumed’?

Author comment 37:

Yes, “we assumed” is what we meant, but we found that we can delete this part of the sentence.

Author change in the text 37:

P13 L32:” 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.”

Referee comment 38:

P10 L17: report the statistical results (test and test statistics)! This goes for all ‘significant’ (or non-significant) results.

Author comment 38:

Indeed, we missed to provide detailled information of the statistical test result. However, in the context of the revision, we decided to omit statistical tests.

Referee comment 39:

P11 L1: ‘The RH..’What RH? It is generally not always clear in the text what parameter you are talking about: daily means, monthly means, something else?

Author comment 39:

This section deals with the 'annual fluctuations of monthly mean values'. Accordingly the RH should be understood as the monthly mean. However, this sentences (P15L9) was omitted in the context of the revision.

Referee comment 40:

P12 L25: word missing

Author comment 40:

Done.

Author change in the text 40:

P17 L13: "At 23 m height, also the daily amplitudes tended to be higher during the dry compared to the wet seasons, whereas for the mosses at the lowest height levels the amplitudes tended to be higher during the wet season. For bryophyte communities at the other height levels the *amplitudes during the different seasons* were less clear.

Referee comment 41:

P13 L16-18: it would be relevant to mention whether such high temperatures were ever reached in wet bryophytes; I would expect that they would only occur while samples were dry.

Author comment 41: Your assumption indeed is right. We included Figure S8 (see below) showing the relation of temperature and water content at different heights along the tree and mentioned the temperature/WC relation in the text.

Author change in the text 41:

P24 L6: "Thus, the temperature did not seem to be a limiting factor for the physiological activity of epiphytic bryophytes in this environment (Fig. S8)."

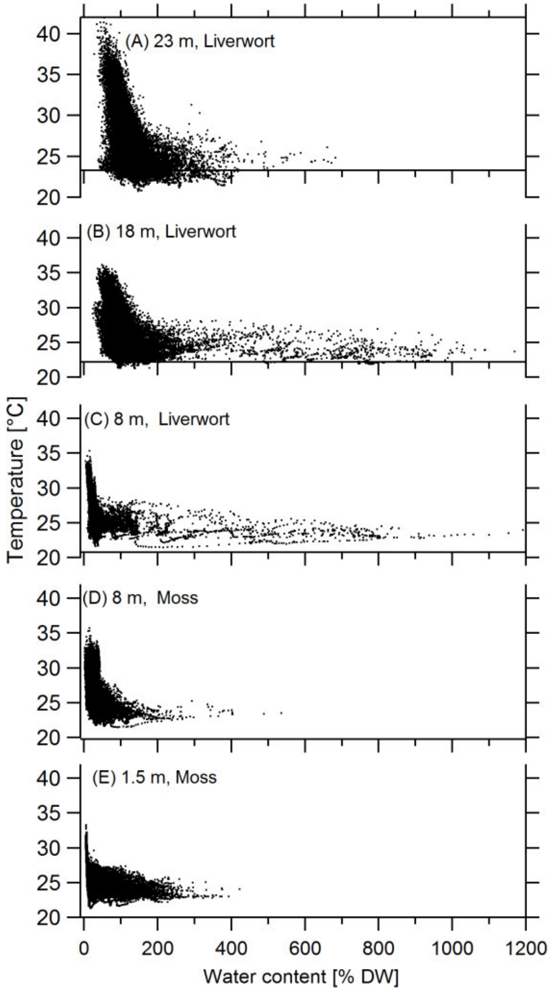

Figure S8: Temperature condition of bryophytes related to their water content. The temperature was measured in bryophytes at different height levels along the tree. Data presented as 30-minute averages.

Referee comment 42:

P13 L 27: I guess you mean the LOWER end of the WCPl range?

Author comment 42:

Yes, indeed.

Author change in the text 42:

P25 L34:" Whereas the *lower* end of the WCP range (30 % DW) is reached during 100% of the time by the liver-worts…

Referee comment 43:

P14 L6: you mean ‘height’, not ‘altitude’ here.

Author comment 43:

Yes, it should mean ‘height’.

Author change in the text 43:

P19 L9: “The microclimatic conditions experienced by bryophyte communities along *a height* gradient at the ATTO site followed…”

Referee comment 44:

P14 L6-7: ‘The microclimatic conditions experienced by bryophytes along an altitudinal gradient at the ATTO site follow the meteorological characteristics to some extent’ - this needs some reference to time…

Author comment 44:

This was meant in a more general way and we think it makes sense to get somewhat more specific for the different sensor types and heights. Thus, we added a sentence as outlined below.

Author change in the text 44:

P19 L9: “The microclimatic conditions experienced by bryophytes 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 water content and temperature readings mostly followed the patterns of the meteorological parameters precipitation and temperature, the light intensities were clearly altered, particularly at the lower levels of the canopy. ”

Referee comment 45:

P14 L15-17: mention in methods

Author comment 45:

It is a good idea to provide this information in the methods section. We also rephrased this sentence in the discussion.

Author change in the text 45:

P7 L23: “*The sensors were installed at the following orientation: at 1.5 and 8 m vertically along the trunk, at 18 m at the upper side of a slightly sloped branch, and at 23 m at the upper side of a vertical branch*.”

P19 L19: “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 at 23 m they were positioned on the upper side of a vertical branch*.”

Referee comment 46:

P14 L18: ‘may have periodically shaded the organisms‘: it seems to me that you can have observed whether this was the case or not: were any leaves situated close to these sensors? (Same for P16 L7-8)

Author comment 46:

As the sensors were located at 8, 18, and 36 m height, they were out of direct sight for us. One would have needed to install cameras to explore this over time. Maybe it is better to use the expression “may” instead “can”.

Author change in the text 46:

P 19 L24: “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.”

Referee comment 47:

P14 L20: was PARavg not the monthly average? Do you mean the monthly averages of the daily patterns?

Author comment 47:

We intended to differentiate between *PARavg* and *PARmax*. While PARavg is the average of a certain period, then specified for the duration, i.e. month or hour, the PARmax is the maximum PAR value reached per day. In the cited context it is the hourly average presented for the diel cycle.

Referee comment 48:

P15 L9-15: this could indeed be expected and is not very exciting. Your contribution here should be discussing the differences in temperature fluctuations quantitatively.

Author comment 48:

Yes, this is a good point and was considered by insertion of some more detail on this difference.

Author change in the text 48:

P15 L17: “*The daily amplitude of the temperature was about twice as large in the canopy as compared to the understory (Tab. S6).*”

Referee comment 49:

P15 L17-18: mention this reinstallation in the methods too.

Author comment 49:

The reinstallation is mentioned in the methods part according to your advice.

Author changes in the text 49:

P8 L5: “However, during stormy episodes and/or physical friction, some WC and temperature sensors fell out of the moss samples and required a reinstallation. Accordingly, the WC sensor 6 (1.5 m) was repositioned in January 2015, WC sensor 1 (1.5 m) in November 2015, WC sensor 1, 6 to 24 and all temperature sensors in November

2016. The periods when the sensors have not been installed in the bryophyte samples were excluded from the data set.*”*

Referee comment 50:

P15 L21-22: mention and discuss this earlier on.

Author comment 50:

This is a good point, and thus, a description of the uncertainty of the WC is now already provided in the material section.

Author change in the text 50:

P8 L12: “Besides the specific position in the substrate, the WC also depended 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.”

Referee comment 51:

P15 L33-34: Is the canopy so open that the wind direction is noticed at 8 m height? Why did you choose the west side, I would expect you to select a side with good moss cover. Interesting if this happened to be the west side if this side receives less moisture. Can you explain this?

Author comment 51:

Yes, the west side indeed was chosen as we found the best bryophyte cover there. Although the wind intensity is weaker inside the canopy, we still experienced wind below the canopy and think that this could have an impact on water and habitat conditions at the different expositions, which then could have an effect on the differential growth of bryophytes.

Author change in the text 51:

P21 L10: “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., 2018). At 8 m height, the investigated bryophytes were exposed to the west, and thus were only sometimes directly influenced by precipitation.”

Referee comment 52:

P16 L11: why does a light rain facilitate drying??

Author comment 52:

Maybe we expressed it in the wrong way. But we intended to say, that after a light rain event the bryophyte samples dried quicker again, as they got not completely saturated with water. We rephrased this sentences for clarification.

Author changes in the text 52:

P21 L24: "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 cause no complete water saturation of the bryophytes. Consequently, the organisms dry much quicker than after a strong rain event that fully saturates the community."

Referee comment 53:

P16 L17: this has at best been estimated, and please specify what you mean by 4%: 4% of water input for bryophytes (or other epiphytes?), or just comprising (thus not 'providing') 4% of total precipitation?

Author comment 53:

This means, it was estimated that approximately 4 % of the total precipitation will reach the ground as stemflow water. Thus, 4 % of the rain water is directly available for epiphytic organisms. By our calculations, this means that 68 to 75 mm per year are available as stemflow water. We rephrased this sentence accordingly.

Author change in the text 53:

P21 L34: "It has been *estimated* that in tropical forests 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 for the years 2015 and 2016 at the ATTO site."

Referee comment 54:

P16 L22: the water holding capacity is not what you have been measuring…Otherwise, this sentence is very true: the high water contents may be due to the high water-holding capacities of these species.

Author comment 54:

Indeed we did not measure the water holding capacity or only indirectly during the calibrations. Instead, we found high water contents over prolonged times, which we wanted to describe here. We rephrased this sentence for clarification.

Author change in the text 54:

P22 L5: "The high WC of the bryophyte samples in the canopy might be partly explained by the different water holding capacity of different bryophyte species (Lakatos et al., 2006; Romero et al., 2006; Williams and Flanagan, 1996)."

Referee comment 55:

P17 L13-14: be careful with your wording: understorey species are probably more efficient at low light (lower LCP), but it would be weird if they had a higher potential photosynthesis.

Author comment 55:

We meant to say that understory species reach higher net photosynthesis rates at low light conditions. We changed this sentence accordingly.

Author change in the text 55:

P23 L15: "…and it has been reported that understory mosses and lichens indeed show higher rates of net photosynthesis *at low light conditions* as compared to canopy species…"

Referee comment 56:

P17 L19-20: words missing

Author comment 56:

Yes indeed. The two sentences were rephrased and linked for clarification.

Author change in the text 56:

P23 L30: "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)."

Referee comment 57:

P17 L22: It may be worth mentioning that Wagner et al 2013 concluded that, although respiration losses may be high, this in itself does not explain low bryophyte growth in tropical lowlands, because respiration rates are adapted or acclimatized to the prevailing temperature conditions: in mosses growing at higher elevations the respiration rates are higher at the same temperatures, but still epiphytic bryophyte biomass is much higher here.

Author comment 57:

Indeed, this type of information can be added to the text.

Author change in the text 57:

P24 L10: "Similarly, Wagner and coauthors (Wagner et al., 2013) stated that the temperature likely was not a limiting factor for NP and growth of the bryophytes investigated by them in a lowland and highland rainforest in Panama.""

Referee comment 58:

P18 L4: another example of a mismatch between cited literature and interpretation: you suggest that it is relevant that water contents in Zotz et al 1997 were measured during the same time of the year, but as this was a different region and a very different forest type, this temporal coincidence has no meaning whatsoever!

Author comment 58:

Yes, indeed the study of Zotz et al. 1997 was performed in a lower montane forest at an altitude of 1100 m, thus we decided to omit the comparison of the WCs.

Referee comment 59:

P18 L13-14 ‘whereas in the canopy, rain events, fog, and condensation seem to be equally important water sources for cryptogams.’ What do you base this conclusion on??

Author comment 59:

Based on the new calibration and calculation of the bryophyte water content (WC) the relation of the WC of bryophytes at different heights changed and required a new interpretation of WC levels. The conclusion, as it was in the previous version, has been removed.

However, we had a closer look at the fog events and can show some humidification of the bryophyte communities upon fog events.

Author change in the text 59:

P16 L15: “Nightly fog might serve as an additional source of water, as the WC of the bryophyte communities increased upon fog events (Fig. S7).”

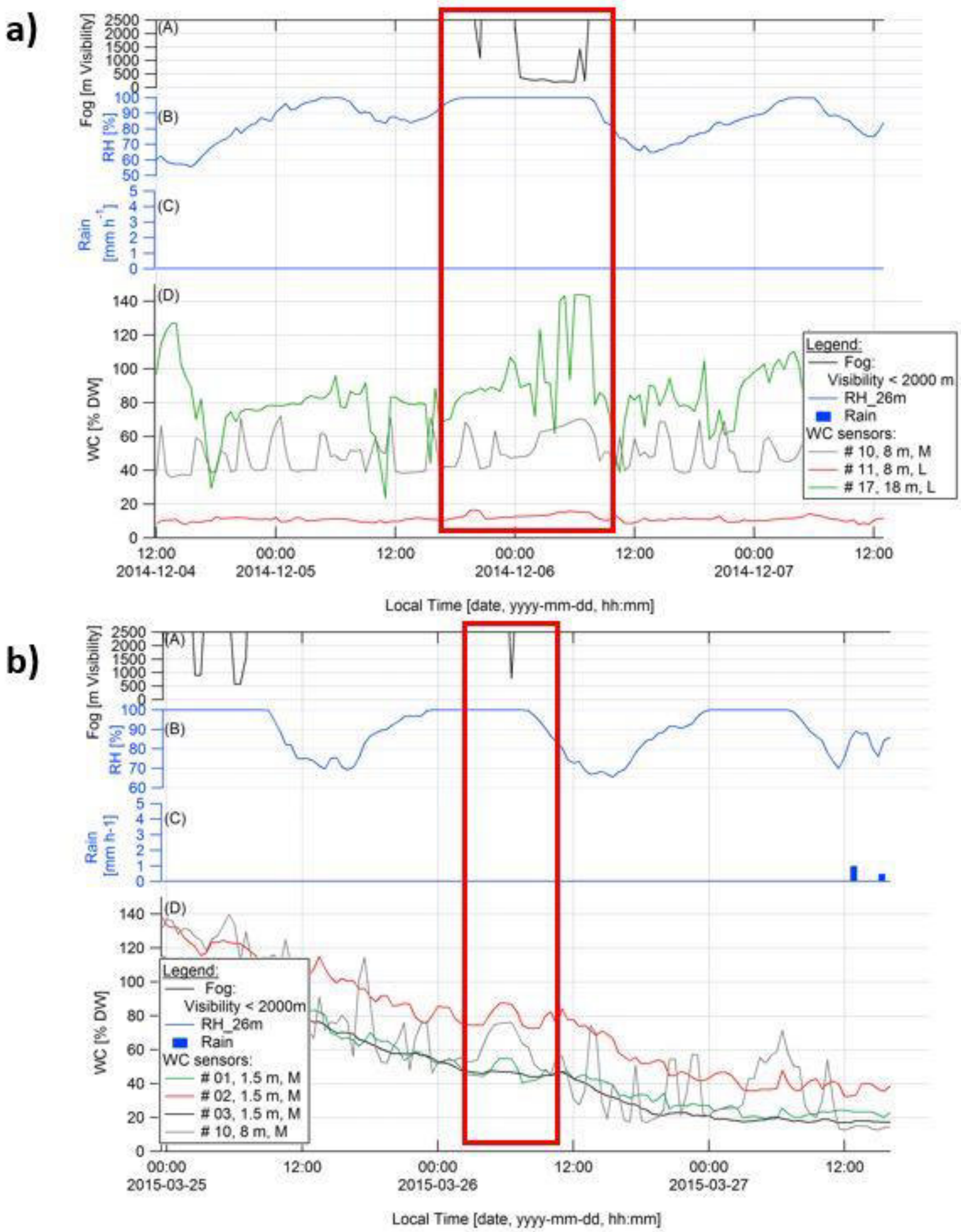

Figure S7: Two exemplary fog events and the reaction of the moisture sensors of the bryophytes (a and b). Each panel presents (A) a fog event defined by a visibility < 2000 m, (B) relative air humidity (RH), (C) rain, and (D) the water content (WC) of the bryophytes. In each panel, the fog event of interest is marked by a red box. For the WC sensors the number, height of installation, and division (M = Moss, L = Liverwort) are given.

Referee comment 60:

P18 L16: what does ‘which’ refer to? The reference seems strange here. (Figure 2: the wet season data are shown twice, the dry season data are missing! A legend is also missing.) → Already corrected by authors

Author comment60:

“Which” refers to the observation of Pardow and Lakatos (2013), where they describe that understory species are more sensitive to drought than canopy species.

However, the sentences has been removed, due to reorganization of the section.

Referee comment 61:

Figure S2: in what way are these integrals? Do you mean interpolations?

Author comment 61:

The data with 30-minute time intervals are the average values of six 5-minute grid data. It indeed is better to say “*average*” instead of “integral” (Figure S4).

Referee comment 62:

Supplement: P4 L7: looks like 2 replicates for *Octoblepharum*

Author comment 62:

Supplement previous Figure S3: Yes, indeed there were two replicates for *Octoblepharum*. However, this calibration is not valid anymore and was deleted in the context of the revision.

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Maaike Bader as referee submitted the comments RC1 and RC3

Maaike Bader RC3

Received and published: 19 February 2019

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.

Referee comment 1:

An additional consideration: an alternative way to use the electrical resistance measurements

Dear authors,

After some more thought and discussion with some colleagues, with whom we will be installing a similar system to measure moss wetness, I would like to suggest using more caution in the translation of the electrical resistance to moss water content and to propose an alternative way of interpreting the measurements. This is giving away the method we intend to use ourselves, which I think may be a good alternative for your study also. You are welcome to cite me for the idea if you think it appropriate.

It is clear that there is a very wide range of moss water-content (WC) values that may be indicated by any electrical resistance value measured. The values are more constrained for the cushion species (Leucobryum), which makes sense seeing that such a life form is denser and more homogenous than the other species, which are prostrate or consist of loosely scattered turf, if I am not mistaken. With such inhomogenous substrates, with different amounts of air and tissue between the probes for each sample, it is no wonder that the measured conductance is widely scattered within species. I think you should reconsider whether you should really try to deduct an absolute value of WC from these measurements. It looks like this is not really possible for most species.

It seems that the points within each calibration curves are nicely ordered, however. Therefore an alternative approach would be to only look at the changes in electrical conductivity, which should reliably indicate changes in water content. With this, you can deduct for any time period whether the samples were drying out or being wetted. When stable at low conductivity, this indicates that the samples are dry (in equilibrium with air humidity), when stable at high conductivity they must be completely wet during rain or fog events. If you have good data about the maximum water content of the species, you might even be able to interpolate between the stable low and the stable high, considering that drying tends to follow relatively smooth extinction curves, as you will see when plotting your calibration curves against time.

I hope this suggestion is of use.

Author comment 1:

Thank you very much for this good and helpful comment. After an intense re-analysis of our field and calibration data we decided to indeed use a calibration approach very similar to the suggested one. We explain this in our response to RC1 in comment 13: We performed a new approach for the calibration of the water content, based on the maximum and minimum values of electrical conductivity reached in the field and the maximum and minimum of the water content reached during the laboratory measurements. With the new approach we assume that the maximum electrical conductivity achieved in the field corresponds to the maximum water content, which could be reached by the organism (and which had been determined during the laboratory experiments). The measurements of the electrical conductivity in the laboratory are not considered anymore. For that, the entire calibration process and the subsequent results were re-calculated again.

Anonymous Referee #2 submitted the comments RC2

RECEIVED AND PUBLISHED: 15 FEBRUARY 2019

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

General referee comment:

The authors provide a description of bryophyte occurrence and microclimate in a tropical forest canopy. These data are scarce and therefore crucial for a variety of applications that the authors list at various times in the manuscript.

General author response: We would like to thank reviewer 2 for his/her appreciation of the microclimate data and the productive comments, which helped us to substantially improve our manuscript.

Referee comment 1:

First, amongst these are poor organization and a general lack of coherence. Facts about bryophytes (such as they are poikilohydric) are repeated often. No clear hypotheses or research questions are outlined. The introduction tells us that bryophytes are 'cool' and important to study but doesn't do a good job of setting up the study itself. Until the end of the methods section, I didn't realize that gas exchange measurements were not performed (something that is mentioned in abstract- If gas exchange in epiphytes is essential, why did the authors not make these measurements?).

Author comment 1:

In the introduction, our aim was to introduce the ecosystem and study site, the invested organisms and communities, and also the measurement approach. As this aim seems to be only partly fulfilled, we thoroughly checked and restructured the introduction. Specific changes were made to bring more clarity into the abstract and the methods section to facilitate an understanding of the study. CO_2 gas exchange measurements indeed would have been interesting, but go beyond the scope of the current study. They make up a major study by themselves, which should be conducted in the near future. For now, we used reliable literature data to investigate the activity patterns of bryophytes when respiration and photosynthesis potentially take place.

Author changes in the text 1:

P2 L7: "In this study, we present data on the microclimatic conditions, including water content, temperature, and light intensities 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."

P2 L26: "These data may be used as a starting point to investigate the role of bryophytes in various biosphere-atmosphere exchange processes, such as measurements of CO_2 gas exchange, and could be a tool to understand the functioning of the epiphytic community in greater detail."

Referee comment 2:

While I am quite satisfied by the measurement protocols and methodology (and that the epiphyte wetness-drying data are novel and important) the study ends up being merely a data reporting exercise with conclusions that often seem unsubstantiated by the data that are presented. Other times conclusions are trivial. For instance, Pg 18, lines 18-23 it is suggested that it is dark in the understory and therefore photosynthesis is light limited. I do not think that today one needs to go to the Amazon to make this conclusion, as this has been known for decades (for e.g. read classic reviews by Chazdon and Fetcher, 1984; Mooney et al., 1984). I seem facetious here, but the authors could use the same data to build upon these earlier findings, and find some nuance and/or insights. What is the knowledge gap that you are trying to fill with your measurements?

Author comment 2:

The main results and conclusions were revised by us to present the data in a more logical and substantiated way. We also utilized the literature offered by you, as it helped to arrange our results in a better framework. In our opinion, one major advantage of our study is, that we performed long-term measurements (running continuously over more than two years) at several heights along a trunk, thus obtaining a vertical profile of the conditions within the vegetation. We now highlight this aspect, apart from other aspects, and with this new structure, we think we can emphasize and improve its significance.

Author changes in the text 2:

P4 L8: "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, few reports can be found in the literature. There is a lack of information regarding the functioning of such communities in an environment with an almost constant high relative humidity and temperature range. Thus, with the long-term continuous measurements presented here, we aim to provide data on seasonality patterns and the vertical profile of the microclimate within the canopy. In the current study, we present the microclimatic conditions, comprising the temperature, light, and WC of epiphytic bryophytes communities along a vertical gradient and an estimation of their activity patterns in response to annual and seasonal variations of climatic conditions."

Referee comment 3:

I want to be clear that I do not think that this work is unpublishable, rather a considerable amount of work needs to be done, especially in the writing, to ensure that it is. The advantage of the study is that the authors have collected a vast amount of important data, and there are several questions that can be formulated and answered. For instance, Fig S.5 is very interesting, and one could speculate about the significance of Tair -TCryptogram relationship in different parts of the canopy, and its significance to physiology. Another question could be the importance of light flecks, since you have carefully measured PPFD within the canopy. Fog is also measured but these data seem largely ignored (I wonder if you had leaf wetness sensors, those data could bolster the study tremendously). I would recommend the corresponding author to read some of the classic literature on epiphyte distribution and abundance (e.g. Benzing, 1984). With some more data exploration and thought I think this could be a very significant contribution. In its current form however, the manuscript reads like an early draft of a thesis or a dissertation chapter, and I do not see it fit for publication in Biogeosciences, or a journal of similar repute.

Author comment 3:

We appreciate this criticism and now put more effort into the analysis and interpretation of the long-term data collected by us.

The relevance of fog was investigated in more detail and its relevance for the WC of the bryophytes is illustrated in the text and in Fig. S7, as shown below. We also analyzed light flecks in the updated version. Unfortunately, no leaf wetness sensors have been installed, so this kind of data cannot be used.

Author change in the text 3:

P16 L15: "Nightly fog might serve as an additional source of water, as the WC of the bryophyte communities increased upon fog events (Fig. S7)."

P24 L21:" 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 bryophyte WC could also increase upon fog (Fig. S7), 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)."

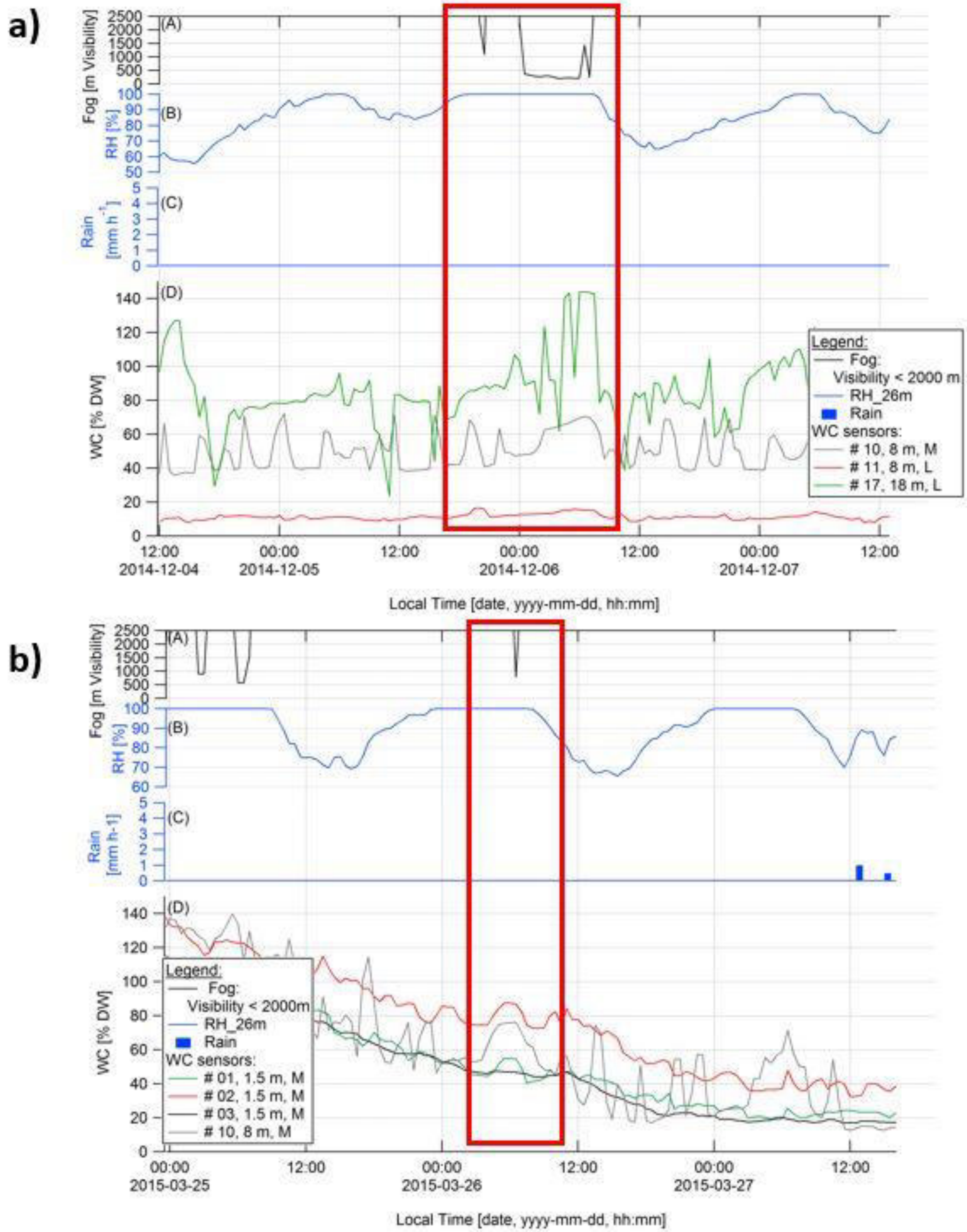
a)
Fog [m Visibility]
(A)
RH [%]
(B)
Rain [mm h-1]
(C)
WC [% DW]
(D)
Legend:
Fog: Visibility < 2000 m
RH_26m
Rain
WC sensors:
10, 8 m, M
11, 8 m, L
17, 18 m, L
12:00 2014-12-04
00:00 2014-12-05
12:00
00:00 2014-12-06
12:00
00:00 2014-12-07
12:00
Local Time [date, yyyy-mm-dd, hh:mm]
b)
Fog [m Visibility]
(A)
RH [%]
(B)
Rain [mm h-1]
(C)
WC [% DW]
(D)
Legend:
Fog: Visibility < 2000m
RH_26m
Rain
WC sensors:
01, 1.5 m, M
02, 1.5 m, M
03, 1.5 m, M
10, 8 m, M
00:00 2015-03-25
12:00
00:00 2015-03-26
12:00
00:00 2015-03-27
12:00
Local Time [date, yyyy-mm-dd, hh:mm]

Figure S7: Two exemplary fog events and the reaction of the moisture sensors of the bryophytes (a and b). Each panel presents (A) a fog event defined by a visibility < 2000 m, (B) relative air humidity (RH), (C) rain, and (D) the water content (WC) of the bryophytes. In each panel, 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.

Referee comment 4:

Finally, authors should provide data access via a link with a doi to a data repository. I wonder if this is required of papers that are submitted to Biogeosciences.

Author comment 4:

The database on the water content, temperature, and light conditions of epiphytes is uploaded to the ATTO data portal (www.attoproject.org/).The data thus are maintained, obtain a doi and can be retrieved from that site.

Specific/Minor comments below:

Referee comment 5:

The abstract is a bit long with too many technical or field specific terms that should be introduced (in the introduction), since it makes it difficult to comprehend for the general reader. An example is "While the monthly average mesoclimatic ambient light intensities above the canopy revealed only minor variations: …" This is a well written but complicated sentence for the average reader. Please simplify.

Author comment 5:

The entire abstract was revised for better readability.

Author change in the text 5:

"**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 data 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 fluctuation 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 98 % 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 higher levels were affected by frequent wetting and drying events, those close to the forest floor remained wet over longer time spans during the wet seasons. 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. These data may be used as a starting point to investigate the role of bryophytes in various biosphere-atmosphere exchange processes, such as measurements of CO_2 gas exchange, and could be a tool to understand the functioning of the epiphytic community in greater detail."

Referee comment 6:

Line 12: 1.5 m relative to what (i.e, please include canopy height). For the abstract something general, like 'near-surface' or 'in the understory' is more appropriate.

Author comment 6:

Yes, it is important to set the height of 1.5 m into relation, especially in the abstract. We exchanged "At 1.5 m height" by "in the understory" for more clarity.

Author change in the text 6:

P2 L15: "*In the understory (1.5 m), monthly average*…."

Referee comment 7:

Line 13: instead of saying "low, exceeding less than 8% …" you could say low, remaining below 5 µmol … more than 92% of the time.

Author comment 7:

Yes, it is easier to follow the way you proposed to revise this sentence. We changed it according to your advice.

Author change in the text 7:

P2 L16: "… individual values were extremely low, *remaining below* 3 µmol m^{-2} s^{-1} photosynthetic photon flux density during *more than 98 %* of the time."

Referee comment 8:

Lines 18-19: Dark respiration should occur independent of light (and unless temperatures are very low, which seems unlikely at your site). The references to photosynthesis and respiration are repeatedly incorrect. Photosynthesis and respiration are co-occurring biological processes (in the light), and therefore one may dominate over the other.

Author comment 8:

We agree with the revision, this sentence was expressed in a way, which could easily be misunderstood. As the entire abstract was restructured, this sentence was removed.

Introduction

Referee comment 9:

The first paragraph is a well written introduction to tropical forests, but has little do with the study. Either you should reframe it in the context of epiphytes or omit. Overall, the introduction does not set up the study satisfactorily.

Author comment 9:

The introduction was restructured and sentences were rewritten to better address the topic.

Author changes in the text 9: P3 L2 (Revised 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). In the tropics, epiphytic bryophyte communities widely cover the stems and branches of trees (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 equally 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). 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). It has been described to play important roles in the water cycle, as well as for carbon, nitrogen, and phosphorus fluxes on regional and global scales (Andreae et al., 2015). However, it is also hard to predict, to which extent the ongoing and envisioned changes will still ensure its ecological services as “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, few reports can be found in literature. There is a lack of information regarding the functioning of such communities in an environment with an almost constant high relative humidity and temperature range. Thus, with the long-term continuous measurements presented here, we aim to provide data on seasonality patterns and the vertical profile of the microclimate within the canopy. In the current study, we present the microclimatic conditions, comprising the temperature, light, and WC of epiphytic bryophytes communities along a vertical gradient and an estimation of their activity patterns in response to annual and seasonal variations of climatic conditions. “

Referee comment 10:

Pg 3 Line 13: ‘By’ not ‘In’ 2013.

Author comment 10:

Changed accordingly (P3 L21)

Referee comment 11:

Pg 4 Line 5: Update references to carbonyl sulfide: (Gimeno et al., 2017; Rastogi et al., 2018).

Author comment 11:

Many thanks for the provision of these additional references, but due to a revision of the introduction, the information on OCS has been omitted.

Methods

Referee comment 12:

Sec. 2.1. A greater description of the site is required. I would recommended starting with site characteristic and then describe the tower and measurements, not the other way around.

Author comment 12:

The advice to start with a description of the forest area and to subsequently characterize the study site itself is a good idea, and we reordered section 2.1 accordingly. However, we refrain from giving a more detailed description of the site, as this is nicely presented by Andreae et al. (2015), which belongs to the same special issue (on ATTO) as the current manuscript.

Author change in the text 12:

P6 L3:"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) (Pöhlker et al., 2018). 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. "

Referee comment 13:

Pg 4 line 13: Remove "The".

Author comment 13:

The word was removed.

Author change in the text 13:

P5 L11: "*Measurements* were conducted at…"

Referee comment 14:

Pg 7 line 2: "were measured" not "are being measured".

Author comment 14:

Done.

Referee comment 15:

P5 Line 5: this seems important for your study and you should describe why sensors were placed where they were placed, in addition to citing the Mota de Oliveira (2013) study.

Author comment 15:

We placed the sensors along a vertical gradient ranging from the understory to the canopy, in order to cover the range of microclimatic conditions experienced by the epiphytic bryophytes as thoroughly as possible. We included a phrase to express this intention.

Author change in the text 15:

P7 L4: "The sensors were placed along a vertical gradient at ~ 1.5, 8, 18, and 23 m above the ground, corresponding to the zones 1 to 4 used by Mota de Oliveira and ter Steege (2015), to investigate the variation within the story structure of the forest.."

Referee comment 16:

Pg 6: line 30: Why 60 C? Is this a temperature that these communities experience?

Author comment 16:

Drying the organisms at 60°C until weight consistency is a common procedure to determine the dry weight of these organisms. This is not related to the environmental field conditions, but is a standard method used to obtain a standardized dry weight.

Author change in the text 16:

P9 L4: "The dry weight (*DW*) was determined after drying at 60 °C *until weight consistency was reached (Caesar et al., 2018)*."

Referee comment 17:

Sec 2.5. Again, some information (a figure ideally) describing the vertical profile of the forest is necessary. That helps put the various sensor heights in perspective.

Author comment 17:

This is a good idea and we prepared a graphical scheme, which is presented in the supplement as Fig. S2 (see below).

Author changes in the text 17:

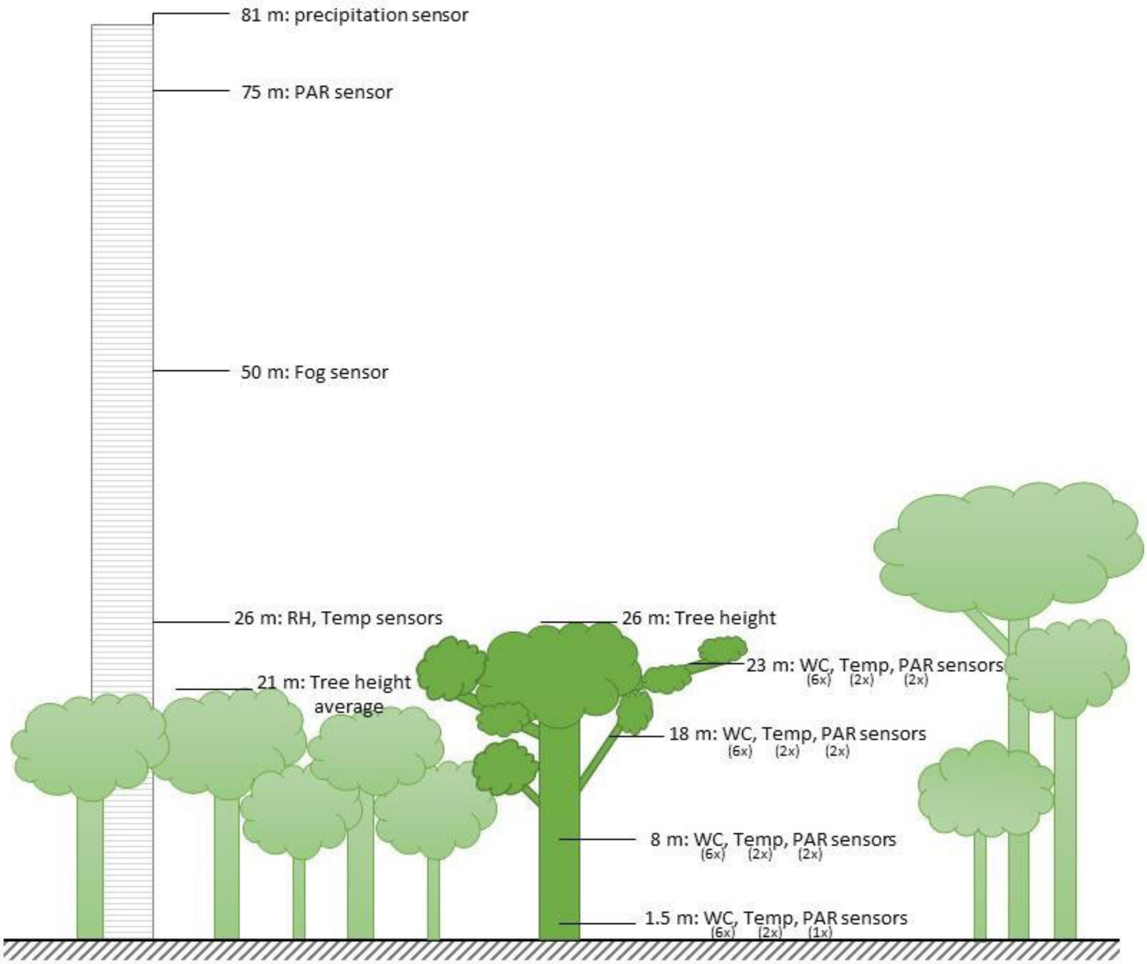

Figure S2: Schematic overview of the sensors installed at different height levels below, within, and above the canopy. The parameters water content (WC) and temperature (Temp) were measured within the bryophyte samples, the light sensors (PAR) were installed directly on top of the thalli. The average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

Referee comment 18:

Lines 15-21: Why were rainfall values gap-filled? Also, isn't the sensor at 1.5 m the least well placed to record rain event. For instance, a small rain event might not even be recorded at 1.5m, as interception must be high in a high LAI forest. Alternatively, there could be time lags between when rainfall occurs at the canopy top and when it is measured by the 1.5 m ht rain gauge.

Author comment 18:

Unfortunately, over the course of the long-term rainfall measurements there are some measurement gaps, which needed to be filled in order to correctly analyze the data.

The rain gauge has been installed at 81 m height on the tower, while the canopy height in this forest is approximately 21 m. Consequently, the rain gauge is placed well above the canopy. As correctly assumed by you, the bryophytes in the understory (1.5 m) might not get watered by light rain events and there is also a delay of several minutes until they get wet compared to the canopy organisms.

<u>Referee comment 19:</u>

Pg 8 L32- Pg 9, L1: Rephrase sentence. Light intensity regulates the balance i.e. the net exchange between photosynthesis and respiration.

<u>Author comment 19:</u>

The sentence was rephrased to clary that light triggers, which process might dominate the carbon balance.

<u>Author change in the text 19:</u>

P12 L32: "While the availability of water determines the overall time of physiological activity, the light intensity regulates *whether* net photosynthesis (NP) or dark respiration (DR) *will dominate the overall metabolical balance*. "

<u>Referee comment 20:</u>

Line 14: Respiration takes place at all light levels. IT IS NOT A LIGHT DEPENDANT PROCESS (there can be significant inhibition of respiration at high light levels). Please check this basic tenet of biology.

<u>Author comment 20:</u>

We are aware of the fact that this was not expressed in a correct way. We meant to state that under these condition NET respiration is observed. We know that both photosynthesis and respiration often occur simultaneously and that the net balance is what is being measured. We changed that accordingly.

<u>Author change in the text 20:</u>

P13 L15: "At light intensities below the compensation point and WCs above WCP, respiration rates are higher than NP rates, causing overall net respiration to occur."

<u>Referee comment 21:</u>

Line 21: Based on *literature*, not literature *data*. Also, please cite the relevant literature.

<u>Author comment 21:</u>

We believe that literature data (i.e. data extracted from the literature) is the correct expression here, however, due to revision of the text this sentences was changed. We added the relevant literature citations.

<u>Author change in the text 21:</u>

P13 L22: "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)."

Results: Overall, I do not have issues with the content per se, but as I have stated before this section needs to be majorly revised/expanded. Some minor comments below.

Referee comment 22:

Pg 10 Line 8: Micromet did not depend on years but varied amongst years.

Author comment 22:

Indeed we were not precise enough with our formulation. We rephrased the sentence accordingly.

Author changes in the text 22:

P14 L14: "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."

Referee comment 23:

Pg 10 Line 18: please define mesoclimate the first time you use this term.

Author comment 23:

Mesoclimate is a standing term describing the climate of a given habitat, covering a side length of some tens or hundreds of meters. We utilized this expression to distinguish the above-canopy climate measurements from the microclimate measurements conducted next to/within the bryophyte thalli. As this expression lead to some confusion, we replaced it by the term "above-canopy climate" throughout the text.

Referee comment 24:

Pg 11 Line 30-31: What does this mean? Please elaborate.

Author comment 24:

(Now P16 L11) At 1.5 m height the water content sensors always showed an increase after rain events, whereas this was not always observed for the sensors at the other height levels. This seems not fully logical at first sight, but we can imagine that the thalli growing on one side of the tree are sometimes not reached by a rain event if it mainly comes from the other side. We could imagine that the rain intercepts with some inclination at the higher levels, whereas close to the ground this inclination is lost. This, however, is only one potential explanation which has not been verified by us.

Referee comment 25:

Pg 12 Sec 3.1.3 header: remove parenthesis

Author comment 25:

Yes, we can remove the parentheses in the header.

Author change in the text 25:

P16 L17: "3.1.3 Diel cycles in different seasons and years along a vertical gradient"

Referee comment 26:

Pg12 Line 13: which 'organisms'. Please specify.

Author comment 26:

Here, the epiphytes, which have been mentioned earlier in the sentence, are meant. In the context of revision this sentence was omitted.

Referee comment 27:

Sec. 3.2. The scope of your inference is limited since you do not have replicates on different trees. I do not see this as limitation, but somewhere (probably in the discussion) you need to talk about heterogeneity in the microclimatic environment.

Author comment 27:

Yes, this is right, and we now describe this restriction of the measurements in an additional passage in the Material and Methods section.

Author change in the text 27:

P 7 L12: "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."

Referee comment 28:

P13 Lines 13-14. This has been mentioned previously (in Sec. 3.1.).

Author comment 28:

Whereas in the previous sections, we discuss the annual fluctuations of monthly mean values and the seasonal changes between the wet and dry season, the diel cycles are in the focus of the current section. Thus, the temperature needs to be discussed under these different aspects and this might give the impression of some repetition. However, we could not find the position where this statement has been made before. Perhaps you can give us a clearer hint on that.

Referee comment 29:

P13 Lines 25 to Pg 14 line 3: This is a well written paragraph but belongs in the discussion.

Author comment 29:

This section was rephrased, according to recalculations and was moved to the discussion section.

Tables

Referee comment 30:

Table 1: Why are these annual means presented? Why are light levels higher at 23 m than at 18m (again discuss heterogeneity)? I still don't have a good grasp of the canopy structure. I do not understand the sensor placement with respect to the canopy structure. Is the 23 m sensor above the canopy top (~ 21m)? Probably not, since light levels seem too low. Also, there seems to be some confusion between relative humidity and water content.

Author comment 30:

The annual means are presented to show the differences between the years, i.e. to demonstrate that the climatic conditions change from one year to the next.

The light conditions at the different height levels of the canopy are discussed in the discussion section (see below). The canopy structure and sensor positions have been already described above (comment 17). The tree is approximately 26 m high, which is now also mentioned in the methods section (P 7 L6), thus the sensors from 1.5 to 23 m height are located on top of the bryophytes growing on the stem of the tree.

We clarified this by deleting the RH-data, as they do not really fit here.

Author change in the text 30:

Canopy structure and sensor position: P7 L16: "Generally, the WC sensors were placed in four different bryophyte communities being heterogeneously distributed along the four 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 sensors) and *Symbiezidium barbiflorum* (3 sensors), and at 18 and 23 m in *Symbiezidium barbiflorum* (6 sensors at each height level; Fig. S2, Fig. S3). The temperature sensors were installed in the same communities at each height, 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 were observed (Tab. S1). The sensors were installed with the following orientations: at 1.5 and 8 m vertically along the trunk, at 18 m at the upper side of a slightly sloped branch, and at 23 m at the upper side of a vertical branch. Thus, also the orientation at the stem may influence the WC of the bryophyte communities, not only the species and the canopy structure. "

Tree height: P74 L6: "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).

P36 L2: Relative humidity and water content: Table 1:

”Annual mean values and standard deviation (± 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 four height levels and above the canopy (a).”

Referee comment 31:

Table 2. There are no significant differences between seasons for some variables (for e.g., temperature), even though this is alluded to in the results (Pg. 11, line 24).

Author comment 31:

The statement on P11 L24 refers to a significant difference of the temperature between 23 m and above canopy measurements assessed during the dry season, which is listed in Table S5 (now Table 2). In the context of the revision, the statistical tests were omitted, thus no significant differences are presented anymore, but were replaced by “trends” and “tendencies”.

Author change in the text 31:

P 16 L3:” At 23 m height, temperatures within the bryophyte communities were frequently higher than the above-canopy values, and during the dry season even the seasonal average temperature was 0.5°C higher, probably due to surface heating (Tab. S2).”

Figures: Generally, the figures need to be clearer, and larger, since you have several subplots.

Referee comment 32:

Fig 2. PAR and Temperature at different heights are very hard to see. Either summarize differently, or show a mean in this figure and direct to a figure in the supplemental with data from all heights.

Author comment 32:

We tried to adapt the figures for more clarity. See the figures at the end of the revised manuscript below.

Referee comment 33:

Figure 3. This also has too many sub-panels crammed in one figure. In the caption, why do you say ecophysiological, micrometeorological and ambient parameters (the same is actually true of Fig. 1 as well). Which ones are which? Why are they called parameters? What are you trying to parametrize? I make a point about this, because this is one of several instances where words are not chosen carefully. Was humidity not measured at all heights?

Author comment 33:

We are aware of the fact that figure 3 is quite complex and needs some attention to be fully understood. On the other hand, we think that it gives a lot of information and allows direct comparisons between the different parameters and thus we would like to keep it in the current way.

With the term “parameters” we refer to environmental parameters, like temperature, precipitation, light intensity, etc., also called climate parameters or climate factors. We changed the captions to clarify the parameters, which are presented. The relative air humidity was measured at 26 m, just above the canopy, while the water content was measured at all four height levels within the bryophyte cushions.

Author change in the text 33:

Figure 3 (P46 L3): “Mean diurnal cycles of water content (WC), temperature, and light conditions of bryophytes, and above-canopy meteorological parameters …”

Referee comment 34:

Figure 4. The histograms are informative but the information provided in the various shaded regions is extremely hard to follow. In the end, I do not understand what the authors are trying to convey. Why is the y-axis broken in the histograms in the left most panel?

Author comment 34:

Figure 4 was adapted to make it clearer and easier comprehensible.

The y-axis in the left-hand panel (PAR) is broken, as the lowest light intensity was reached at a frequency between 50 and 70%. All the higher light intensities occurred at frequencies of only a few or even below 1%. To show both the high and low frequencies at good resolution, we decided to use a broken y-axis.

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Anonymous Referee #3 submitted the comments RC4

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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.

General referee comments:

Dear Editor, dear authors

I have read with interest the manuscript entitled "Microclimatic and ecophysiological conditions experienced by epiphytic bryophytes in an Amazonian rain forest" by Löbs et al. submitted to Biogeosciences. Please find my comments related to it below:

I appreciate a strong point in this manuscript that is to contribute to raise the data availability regarding cryptogamic covers functional performance in tropical regions, and going further, the lack of data available in Central and South America. It seems that almost all the literature regarding this issue has been focused in Polar Regions some years ago and in drylands at the present. I also appreciate the novelty and the effort made to provide microclimatic data sets at those heights at the tree trunks. If we want to understand properly the relevance of these organisms in global cycles and their response under environmental changes a huge and very different biome as the tropics cannot be ignored. I think that authors do a complete revision of the literature available and try to contribute from there with their data. Mosses dominate cryptogamic covers in tropical regions in biodiversity, so the target organisms in the study seems to be quite correct.

General author response:

We would like to thank the reviewer for appreciating our work and for the efforts spent on our manuscript. His/her comments helped us to substantially improve it.

Referee comment 1:

But, at the same time, my opinion is that this lack of data availability in the region is an intrinsic weakness of the manuscript. My point here is that the manuscript is based in a double assumption rather than in strictly measured data sets. The first assumption would be the water content of the bryophytes through conductivity sensors.

I appreciate the effort made by the authors calibrating this methodology in the lab and this experimental testing gives higher credibility to the measurements. But then we see the big second assumption that is to extrapolate data taken from the literature to understand the functional performance of the bryophytes in the altitudinal gradient. I think that it is likely that possible inaccuracies could arise in this sense. Data available in the literature is little, so, it must be difficult to find similar experimental designs that could help providing reliable extrapolations. I am not talking about finding same species with data available in the literature, but it would be interesting, in order to trust the ecophysiological data provided, to have data from a similar habitat following at least the light adaptation patterns of the species included in this work.

As I suppose that these data sets are very difficult to get, but I think that this manuscript is interesting and useful to the scientific community, I would make a proposal to the authors:

What about to include in your manuscript a few gas exchange checkpoints in the lab including relevant species inside the gradient. For example, one representative species in the understory and another one at the closer point of the canopy could serve as cardinal points to calibrate authors' predictions about net photosynthesis availability, time and amount of respiration and possible C losses, light cardinal points, adaptation strategies. This would improve the discussion substantially from my point of view.

I am not asking for a complete gas exchange profile of the species included in the study because I know how time consuming this technique is, just a few replicated checkpoints in the lab to see how close predictions are from reality. If they were far from each other, the real gas exchange parameters measured could work as a more reliable source of predictions than a very likely imprecise literature for the aim targeted. I would welcome further assumptions at this point, but based in some real measured values (I said in the lab because conditions are easier to control, but some field gas exchange data sound good for me also). I think that this could improve the manuscript and put it as a reference text in tropical epiphytic bryophytes functional performance due to the low amount of literature available.

Author comment 1:

Thank you very much for these constructive ideas on CO_2 gas exchange measurements. It indeed would be good to include some measurements conducted by ourselves. However, from past experiences we know that quick gas exchange measurements might deliver truly misleading results. Just as an example, it has been shown by colleagues, that after transport to the lab, tropical organisms showed only a fraction of the physiological activity previously assessed in the field. The samples had strongly suffered from the transport, as they had to be air-dried prior to the transport in order to avoid molding during that time. Thus, we think that CO_2 gas exchange measurements indeed make sense, but that they also need to be conducted with care. This indeed is planned for the future, but would go beyond the scope of the current study. For the present study, we found some very good data on lowland rain forest bryophytes, assessed by a group, which is well-experienced in CO_2 gas exchange measurements. Thus, for the current study we decided to use their results in order to assess potential physiological activity patterns, but we also stress the potential sources of error and inaccuracy of this approach. We hope that we could convince you of the validity of this approach.

During the review process, we conducted a complete revision of the calibration process for the water content sensors resulting in by far smaller inaccuracies.

Some minor points also to comment:

INTRO

Referee comment 2:

Page 3, Ls 20-25: I would focus in bryophytes functional properties rather than in general physiological features of cryptogamic covers because only bryophytes are included in the experimental design.

Author comment 2:

Thank you for this comment. The whole introduction was revised, with the aim to focus more on the epiphytic bryophyte communities.

Author changes in the text 2:

P3 L 2: “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). In the tropics, epiphytic bryophyte communities widely cover the stems and branches of trees (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 equally 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). 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). It has been described to play important roles in the water cycle, as well as for carbon, nitrogen, and phosphorus fluxes on regional and global scales (Andreae et al., 2015). However, it is also hard to predict, to which extent the ongoing and envisioned changes will still ensure its ecological services as “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, few reports can be found in literature. There is a lack of information regarding the functioning of such communities in an environment with an almost constant high relative humidity and temperature range. Thus, with the long-term continuous measurements presented here, we aim to provide data on seasonality patterns and the vertical profile of the microclimate within the canopy. In the current study, we present the microclimatic conditions, comprising the temperature, light, and WC of epiphytic bryophytes communities along a vertical gradient and an estimation of their activity patterns in response to annual and seasonal variations of climatic conditions. “

METHODOLOGY

Referee comment 3:

-Section 2.5. Could you please explain in more detail why some meteorological parameters are measured at 26m and light is measured at 75m?

Author comment 3:

Monitoring of the meteorological parameters is conducted in the course of the overall ATTO long-term measurements (for more details see Andreae et al., 2015). For this, different sensors have been installed at different heights in order to serve the needs. Ambient (above-canopy) light is measured at 75 m in order to avoid shading of the canopy and also precipitation and fog need to be measured above the canopy (at 81 and 50 m height, respectively). The different height levels are also explained by the different amounts of space needed by the sensors. We see that as uncritical for these parameters, as ambient light intensity, fog, and precipitation should not vary between 50 and 81 m height. For relative ambient air humidity and ambient temperature we decided to use the data closest to the canopy, i.e. at 26 m height.

In the revised version of the manuscript, we provide the information that the meteorological parameters are assessed in the course of the long-term monitoring at the site and we also provide a scheme illustrating the different sensor locations below, within and above the canopy (Supplement Figure S2, see below). We hope this will clarify the sensor setup in some more detail.

Author changes in the text 3:

P12 L7: "For the purpose of long-term monitoring, a set of meteorological parameters is being measured within the ATTO project since 2012."

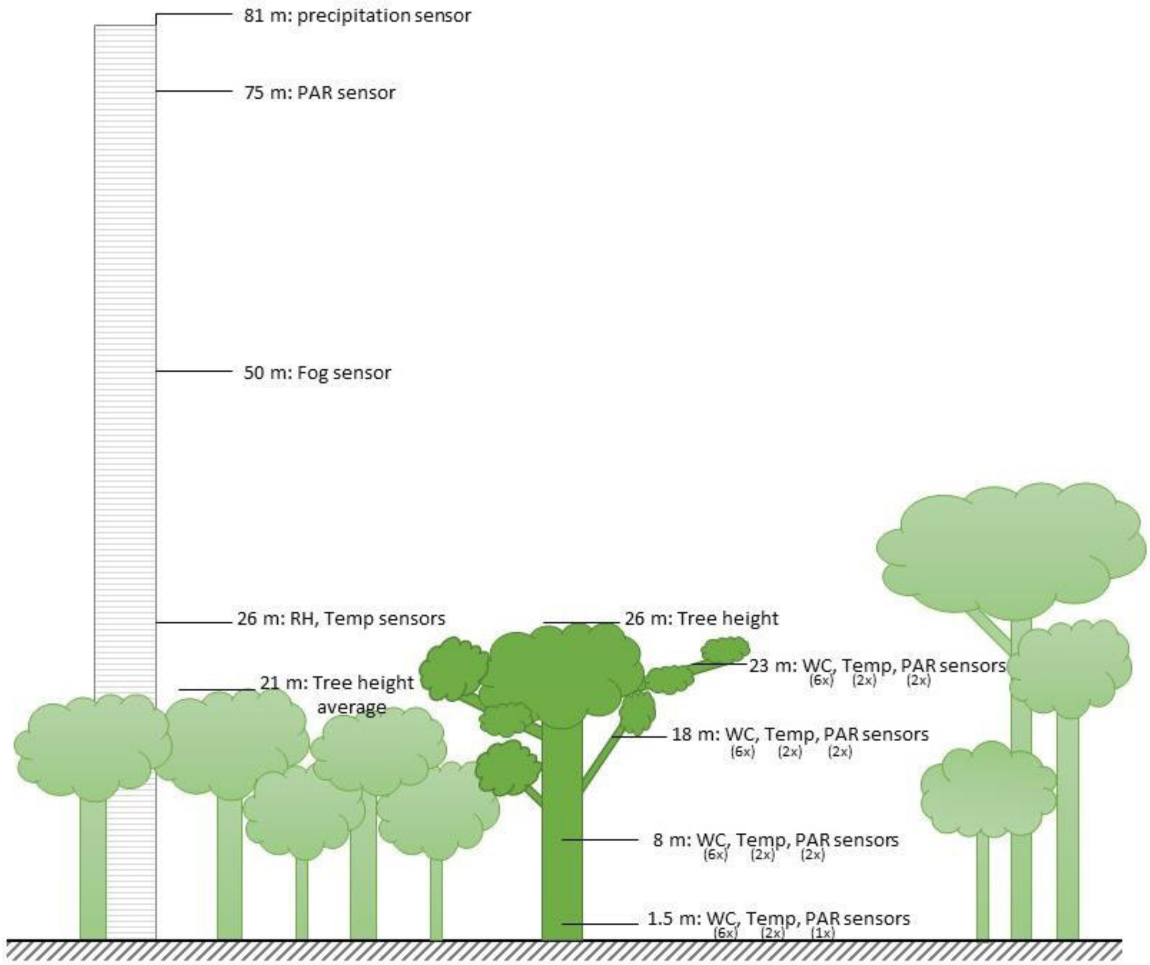

Figure S2: Schematic overview on the sensors installed at different height levels below, within, and above the canopy. The parameters water content (WC) and temperature (Temp) were measured within the bryophyte samples, the light sensors (PAR) were installed directly on top of the thalli. The average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

Referee comment 4:

-Section 2.6. I would establish the possible ranges for each ecophysiological parameter analyzed focusing more in tropical epiphytic bryophytes functional performance.

Author comment 4:

Yes, this entire estimation was revised to restrict the considered values to epiphytic bryophytes of tropical lowland forests. Also Table S3 in its revised version, only shows lowland studies.

Author change in the text 4:

Changes in Table S3.

Table S3: Parameters determining fractional time of photosynthesis and respiration. The lower water compensation point (WCP_l), the lower light compensation point (LCP_l), the temperature for optimal net photosynthesis (T_{opt} NP), and the upper temperature compensation point (TCP) as relevant parameters have been extracted from published studies conducted at lowland sites of tropical rain forests.

Parameter	Low	High	Unit	Reference	Study site
WCP_l	30	80	% DW	Wagner et al 2013	Panama, lowland rain forest, 0 m
LCP_l	3	12	µmol m^{-2} s^{-1} PPFD	Lösch et al. 1994	Zaire, lowland rain forest, 800 m
T_{opt} NP	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

RESULTS

Referee comment 5:

-Section 3.1. 2 consecutive years of microclimatic data availability is a good and interesting output provided by authors

Author comment 5:

Yes, this is a long term monitoring project and the database on the water content, temperature, and light conditions of epiphytes is uploaded to the ATTO data portal (www.attoproject.org/).The data thus are maintained, obtain a doi and can be retrieved from that site.

Referee comment 6:

-All sections in general. I see that the headings do not correspond too much with what is written at each of the sections. Authors mix concepts in the same paragraphs such as microclimate, mesoclimate, water content, seasonal and daily analyses …Would it be possible to rethink the headings of the sections and write text more focused to each of the headings?

Author comment 6:

Indeed, it was not an easy task to structure the manuscript in a logical way and in the end we decided to use a structure to analyze the data according to different time frames (i.e., comparison of years, seasons, diel cycles, etc.). Thus, indeed, different climatic parameters are sometimes used within one paragraph to illustrate their interdependence. However, we also considered this comment and looked over the structure within the paragraphs again. We now avoid mixing different parameters wherever this is possible.

Author change in the text 6:

Some structural changes were made throughout the manuscript in order to obtain an overall better readability.

Referee comment 7:

P 10 L9, I think that authors missed a word after ”35%”, maybe “lower”?

Author comment 7:

Yes, “35 % *lower*”, we added the word.

Author change in the text 7:

P14 L17: “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 S2).”

Referee comment 8:

How did authors compare climate statistically between years/seasons? Did you use a monthly basis? Daily basis?

Author comment 8:

The mean values were calculated from the 5-minute data points. However, in the revised version of the manuscript we decided to omit the statistical tests. Author changes in the text 8:

Table 1: Annual mean values…"Mean values were calculated from 5-minute intervals, except for PAR_{max}, where the daily maximum values were considered."

Table 2: Seasonal mean values…" Mean values for the respective seasons were calculated from 5-minute intervals of the years 2015 and 2016, except for PAR_{max}, where the daily maximum values were considered."

Referee comment 9:

P 10 L 25-26. If I understood ok, the idea is that the microclimatic T value at the moss level was higher than ambient T, and that this is a frequent pattern. What about the shading effect of the tree canopy over microclimatic T?

Author comment 9:

Yes, indeed there is some shading effect of the canopy, which could result in a reduced heating of the bryophytes, also at 23 m height within the canopy. However, also ambient T measurements are always performed in the shade to avoid a short-term impact of direct insulation. Thus, we do not think that there is a large difference in shading. However, we think that wind intensities are reduced within and below the canopy and that the bryophytes have a higher heat storage capacity, which both may cause higher temperatures measured within the bryophytes.

Referee comment 10:

Fig 1, legend. I would say estimated water content of the bryophytes rather than "ecophysiological conditions"

Author comment 10:

The expression "*ecophysiological*" was finally omitted and was changed throughout the text and figures and replaced by "*water content of bryophytes*".

Author change in the text 10:

Figure 1: "Water content (WC), temperature, and light conditions experienced by bryophyte communities, and above-canopy meteorological conditions in the Amazonian rain forest…."

DISCUSSION:

Referee comment 11:

P 14 Ls 22-24. I think that these patterns observed reinforces that measuring some gas exchange control points might be useful.

Author comment 11:

We completely agree that additional CO_2 gas exchange measurements would be of interest. Our hesitation to measure just some cardinal points is explained in the first section of this response letter. We also explain there, that, under the current conditions, we prefer to use a well-established study over quick measurements conducted by ourselves. We prefer to conduct an in-depth CO_2 gas exchange study in the near future, which, however, goes beyond the scope of the current manuscript at hand.

Referee comment 12:

P 4 line 13: Remove "The".

Author comment 12:

Yes, the word was removed.

Referee comment 13:

P 17 Ls 19-23. I do not understand this point properly.

Author comment 13:

This paragraph was adapted to clarify the information. The intention was to express that respiration is more sensitive to temperature than photosynthesis.

Author change in the text 13:

P 23 L27: "The temperature regulates the velocity of metabolic processes, hence it has a strong impact on the respiration, while the photosynthetic light reaction is by far less sensitive (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)."

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Microclimatic ~~and ecophysiological~~ 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~~ing~~ their impact on local, regional, and even global biogeochemical processes.

In this study, we present data on the microclimatic ~~and ecophysiological~~ conditions, including water content, temperature, and light ~~of~~ conditions experienced by epiphytic bryophytes along a vertical gradient and combine these with ~~mesoclimate~~ "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 ~~mesoclimatic~~ above-canopy~~ambient~~ light intensities ~~above the canopy~~ revealed only minor ~~variations~~fluctuation ~~in~~over the course of the year, the light intensities experienced by the bryophytes varied depending on the location within the canopy~~measured at different canopy heights~~ ~~incident on the~~ ~~bryophytes showed different patterns~~ ~~being differently from that.~~ ~~at different heights~~, probably ~~within the canopy~~ caused by~~depending on~~the individual shading by vegetation~~ plays a relevant role~~. In the understory (1.5 m) ~~At 1.5 m height~~, monthly average light intensities were similar throughout the year and individual values were extremely low, ~~exceeding~~ remaining below 3~~5~~ µmol m^{-2} s^{-1} photosynthetic photon flux density ~~only during 8~~during more than 98~~2~~ % 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 w~~W~~ater contents of bryophytes varied depending on precipitation, ~~and~~ air humidity, and bryophyte type. Whereas bryophytes at higher levels were affected by frequent wetting and drying events, those close to the forest floor remained wet over longer time spans during the wet seasons. ~~Based on estimates of the potential duration of net photosynthesis and dark respiration, our data suggest that water contents are decisive for overall physiological activity, and light intensities determine whether net photosynthesis or dark respiration occurs~~~~dominates~~~~, whereas temperature variations are only of minor relevance in this environment.~~ In general, bryophytes growing close to the forest floor ~~are~~ were limited by light availability, while those growing in the canopy ~~must~~ had to withstand larger variations in microclimatic conditions, especially ~~in~~ during the dry season. These data may be used as a ~~prerequisite~~starting point to investigate the role of bryophytes in various biosphere-atmosphere exchange processes~~. For further investigations of the physiological activity patterns~~, such as ~~the~~ ~~M~~measurements of CO_2 gas exchange, and could be a tool~~be extremely helpful~~~~might be~~ ~~are essential~~ to ~~elucidate their physiological activity patterns~~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). In the tropics, epiphytic bryophyte communities widely cover the stems and branches of trees (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 equally 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, ~~they some species~~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 ~~a~~ supra~~er~~saturation, when~~re~~ gas diffusion is restrained, causing ~~a~~ 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~~,~~ ~~as shown for lichens~~ (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~~s~~ 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). 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). It has been described to play important roles in the water cycle, as well as for carbon, nitrogen, and phosphorus fluxes on regional and global scales (Andreae et al., 2015). However, it is also hard to predict, to which extent the ongoing and envisioned changes will still ensure ~~its~~its ecological services as “green lung” and carbon sink of planet Earth (Soepadmo, 1993).

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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 may cause a supersaturation, where gas diffusion is restrained, causing a 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, as shown for lichens (Lange et al., 1996, 1998, 2000; Rodriguez-Iturbe et al., 1999).

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, few reports can be found in- the literature. There is a lack of information regarding the functioning of such communities in an environment with an almost constant high relative humidity and temperature range. Thus, with the long-term continuous measurements presented here, we aim to provide data on seasonality patterns and the vertical profile of the microclimate within the canopy. In the current study, we present the microclimatic conditions, comprising the temperature, light, and WC of epiphytic bryophytes communities along a vertical gradient and an estimation of their activity patterns in response to annual and seasonal variations of climatic conditions.

The Amazon rain forest covers 5 821 800 km² on the South American continent, thus forming the second largest terrestrial vegetation type after the boreal forests of the Taiga (Melack and Hess, 2010). Tropical rain forests are characterized by humid conditions, high temperatures, minor annual fluctuations of temperature, and an immense species diversity of flora and fauna. They have been described to play important roles in the water cycle as well as for carbon, nitrogen, and phosphor fluxes on regional and global scales (Andreae et al., 2015). Tropical rain forests are known to absorb large amounts of solar radiation and convert it to latent heat, thereby cooling and stabilizing temperatures, and to carry moisture into the atmosphere, thus helping to generate rainfall (Lawrence and Vandecar, 2015). Consequently, rain forests are a key player in regional and global nutrient cycling and climate. However, the rain forests are endangered by human activities, such as clear-cutting of primary forests for plantations, livestock, and settlement of residential and industrial areas, but also by atmospheric pollution (Koren et al., 2014; Rosenfeld et al., 2008; ter Steege et al., 2015). Up to now, ~ 16 000 tree species have been estimated for the Amazon (ter Steege et al., 2013), but the impact of anthropogenic activities on these numbers is highly uncertain. Similarly, it is also hard to predict, to which extent the ongoing and envisioned changes will still ensure its ecological services as "green lung" and carbon sink of planet Earth (Soepadmo, 1993).

Apart from vascular plants, forming a predominant fraction of the biomass within this biome, there are also cryptogamic photoautotrophs comprising bryophytes, algae, lichens, and cyanobacteria, which form communities together with heterotrophic fungi, other bacteria, and archaea. These communities 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). In the Amazon 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. In 2013, 800 species of mosses and liverworts, 250 lichens species, and 1 800 fungal species have been reported for the Amazon region . The epiphytic bryophytes in the tropics play a prominent role in environmental nutrient cycling (Coxson et al., 1992; Zotz et al., 1997) and also influence the microclimate within the forest, thus contributing to the overall fitness of the host plants and the surrounding vegetation (Zartman, 2003). However, they are equally affected by deforestation and an increasing 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 they can outlast extreme weather conditions, being reactivated by water (Oliver et al., 2005; Proctor, 2000; Proctor et al., 2007; Seel et al., 1992), and 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 may cause a supersaturation, where gas diffusion is restrained, causing a reduced CO_2 gas exchange rates (Cowan et al., 1992; Lange and Tenhunen, 1981; Snelgar et al., 1981) and even ethanolic fermentation (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). Depending on their habitat, they may be active for only a minor fraction of their entire life, as, e.g., described for deserts (Raggio et al., 2017), where water is only rarely available, and for arctic/alpine regions, where frost limits the water availability (Colesie et al., 2016; Reiter et al., 2008; Schroeter et al., 2011). During nighttime, when only respiration takes place in active organisms, the temperature is highly relevant, as high temperatures may lead to major carbon loss (Lüttge, 2008; Zotz et al., 1997).

It has been shown that despite their inconspicuous growth, cryptogamic communities play a significant role in regional and even global nutrient cycles, as they were estimated to fix ~ 4 Pg carbon per year, corresponding to about 7 % of the annual net primary productivity of vascular vegetation (Elbert et al., 2012). It has also been calculated that they may play a highly relevant role in the global nitrogen cycle by fixing ~ 49 Tg of nitrogen per year and releasing reactive nitrogen compounds as well as the greenhouse gas N_2O into the atmosphere (Elbert et al., 2012; Lenhart et al., 2015). Furthermore, they may contribute to the uptake of carbonyl sulfide (OCS) (Kuhn et al., 2000; Kuhn and Kesselmeier, 2000), the bidirectional exchange of volatile organic acids and aldehydes (Wilske and Kesselmeier, 1999), and other volatile organic compounds (Kesselmeier et al., 1999).

In the current study, we present the ecophysiological conditions and activity patterns of bryophyte communities in response to annual and seasonal variations, as well as along a vertical gradient from the understory to the canopy of the forest. These data are essential to analyze the spatio-temporal effects of cryptogamic communities on particle and trace gas emission patterns.

2 Material and Methods

2.1 Study site

The study site is located ~~– ATTO is located on~~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~~year~~$^{-1}$ (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) (Pöhlker et al., 2018). 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* ~~(plateau forest)~~ forest has an average growth height of ~ 21 meters, a tree density of ~~around~~ ~ 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). ~~The m~~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.)~~in the Amazonian rain forest in Brazil~~, which has been fully described by Andreae and co-authors (2015). It comprises one walk-up tower and one mast of 80 m each, ~~which have been~~ 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. ~~ATTO is located on a *terra firme* forest area, approx. 150 km northeast of Manaus, Brazil. The average annual rainfall is 2 540 mm year^{-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) (Pöhlker et al., 2018). 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 site is located on a plateau of yellow clayey ferralsols (latosols, oxisols) deposited on top of sedimentary layers of the Miocene Barreiras formation (Chauvel et al., 1987).~~

~~The *terra firme* (plateau forest) has an average growth height of ~ 21 meters, a tree density of around 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). Other forest types in the Amazon, such as the *igapó* (floodplain) and *campina/campinarana* (white sand areas), host around 824 and around 1 179 tree species on areas of ~ 100 000 km² and ~ 81 000 km², respectively (Adeney et al., 2016; Andreae et al., 2015; Melack and Hess, 2010; Montero et al., 2014; Sears, 2018; ter Steege et al., 2013, 2015).~~

2.2 Microclimatic conditions within epiphytic habitat

~~The microclimatic~~~~g~~The parameters temperature and light within/on top of the bryophytes and their~~ ecophysiological~~ ~~water content~~WC ~~of bryophytes are being~~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, corresponding to the zones 1 to 4 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 ~~water content~~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 ~~species~~ communities ~~at~~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. Generally, the WC sensors were placed in four different bryophyte communities being heterogeneously distributed along the four 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 sensors) and *Symbiezidium barbiflorum* (3 sensors), and at 18 and 23 m in *Symbiezidium barbiflorum* (6 sensors at each height level; Fig. S2, Fig. S3). The temperature sensors were installed in the same communities at each height, 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~~al~~ WC and patterns of the drying process were observed (Tab. S1~~a~~). The sensors were installed with the following orientations: at 1.5 and 8 m vertically along the trunk, at 18 m at the upper side of a slightly sloped branch, and at 23 m at the upper side of a vertical branch. Thus, also the orientation at the stem ~~can~~may influence the WC of the bryophyte communities, not only the species and the canopy structure. ~~The temperature and the water content~~~~WC~~ ~~sensors were installed within the epiphytic bryophyte~~ ~~communities~~~~, while the light sensors were fixed on ~ 5 cm long sticks and installed next to the bryophyte cushions~~ ~~samples~~ ~~(Fig. S1).~~ Whereas bryophytes were selected as cryptogamic exemplary organisms to be measured, similar microclimatic conditions and activity patterns are expected for all cryptogamic organisms due to their poikilohydric nature (Raggio et al., 2017). Since the installation, automatic measurements at 5-minute intervals ~~have been~~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. ~~For~~

weather protection the logger was placed in a waterproof enclosure (Enc12/14, Campbell Scientific, Logan, Utah, USA), which is additionally sheltered by an external housing.

The water contentWC 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 (without a 90° angle)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. Accordingly, the WC sensor 6 (1.5 m) was repositioned in January 2015, WC sensor 1 (1.5 m) in November 2015, WC sensor 1, 6 to 24 and all temperature sensors in November 2016. The periods when the sensors have not been installed in the bryophyte samples were excluded from the data set.

The WC values are were subject to a fluctuation correspondingoscillating, causing an inaccuracy of tocorresponding to approximately 15 % dry weight (DW). Besides the specific position in the substrate, the WC also dependeds 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 measurement, 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 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. S42). The smoothened data were used for detailed illustrations of seasonal variability (Fig. 2 and S45), whereas the 5-minute data were used for and for data calculations in order to also consider short light fleck events.

2.3 Calculation of the water content (WC)

The water contentWC 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 was designed in the manner that the electric voltage is proportional to the electrical conductivity, which is the inverse resistance, due to the fixed distance between the sensor pins. 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 (% DW). The dry weight was determined after drying at 60 °C until weight consistency was reached (Caesar et al., 2018).

The calibration described procedure below was then applied to the temperature-corrected electrical conductivity values to obtain final water contents, as percentage of the dry weight values and precipitation equivalents, is detailed in the supplement.

2.4 Calibration of the water content sensors

A calibration of the water content sensors was required conducted for all the communities dominated by each of the different bryophyte species. Thus, the same bryophyte species as those where sensors had been installed in (i.e., *Leucobryum martianum* (Hornsch.) Hampe, *Sematophyllum subsimplex* (Hedw.) Mitt., *Symbiezidium* sp.*barbiflorum* (Lindenb. & Gottsche) A. Evans, and *Octoblepharum cocuiense* Mitt.), For this, samples of them were collected in the forest area surrounding the ATTO site. For the sensors at the upper three height levels the bryophyte taxa could not be securely determined. Thus, the bryophyte taxon with the a highest abundance in the canopy of this treecommunities, i.e., the liverwort *Symbiezidium barbiflorum* sp. was used considered for all the further calculation in the course of the calibration, due to its morphological characteristics. Overall, for tropical lowland rain forests in Panama and French Guyana it was shown that liverworts have a higher abundance and higher biomass at the upper trunk and in the canopy than in the understory (Gradstein and Allen, 1992; Mota de Oliveira et al., 2009; Mota de Oliveira and ter Steege, 2015; Pardow et al., 2012; Romanski et al., 2011; Sporn et al., 2010). They bryophytes were removed from the stem with a pocket knife and stored in paper bags in an air conditioned lab container until calibration (few hours to few days after collection). Prior to the calibration, the samples were cleaned from adhering material using forceps.

Subsequently, the water content sensors were calibrated for the different bryophyte species, as, besides the water content, also nutrient content, salinity, thallus structuremorphology, and temperature have an impact on the assessed electrical conductivity (Weber et al., 2016). The calibration procedure largely followed Weber et al. (2016), being conducted in a large metal box (60 x 60 x 41 cm; Zarges, Weilheim, Germany) placed in an air conditioned laboratory container at ~ 26 to 28 °C. The samples were placed on a small Styrodur C block (BASF SE, Ludwigshafen, Germany), which was positioned centrally on a balance (ME403, Mettler Toledo, Gießen, Germany). The sensor was fixed in the Styrodur C block, simultaneously fixing the bryophyte sample on the block. In the beginning of each calibration the sample was wetted to thefull water holding capacitysaturation and during drying of the sample, the values of the balance and sensor were recorded at 60 second intervals. Between the measurement points, a fan placed approx. 10 cm away from the sample was started automatically to cause circulation of the air, thus speeding up the drying process. The measurements were automated by a self-designed program (Docklight scripting) and were continued until the samples reached a constant weight.

Following the measurements, a digital image was taken of each sample and the surface area (*SA*) was determined by means of the software ImageJ (Wayne Rasband, National Institutes of Health, Bethesda, Maryland, USA). The dry weight (*DW*) was determined after drying at 60 °C until weight consistency was reached (Caesar et al., 2018). The water content (*WC*) of the samples was calculated according to the formula in Weber et al. (2016):

$$WC\ [\%\ DW] = \frac{(SW - (SensW + DW))}{DW} * 100\ \% \qquad (3)$$

with *SW* as sample weight [g], *SensW* as sensor weight [g], and *DW* as sample dry weight [g].

The amount of water within the sample can also be calculated as the precipitation equivalent (*PE*), representing the amount of water per surface area stored within the sample:

$$PE\ [\text{mm}\ H_2O] = \frac{SW - (SensW + DW)}{SA * \rho H2O} * 10 \qquad (4)$$

with *SA* as surface area [cm²] and ρH_2O as the density of water [1 g cm^{-3}].

For each of the four bryophyte taxa three replicates (except for *Sematophyllum subsimplex*: four, and *Octoblepharum cocuiense:* two replicates) were investigated and for each replicate four drying cycles were performed. The first cycle of each replicate was excluded from further calculations, as this was needed for the sensor setup to adjust itself. The resulting nine (twelve for *Sematophyllum subsimplex* and six for *Octoblepharum cocuiense*) calibration curves of each bryophyte species were fit either to a linear, a linear with exponential correction, or a quadratic function. As the variations between the replicates of each taxon tended to be large, the determination of the best fit was not trivial (Fig. S3).

The linear fit was calculated according to the following Eq. (5):

$$WC = a_1 * C + a_2 \qquad (5)$$

The linear fit with exponential correction was calculated as follows:

$$WC = \exp(a_1 * C) * a_2 * C + a_3 \qquad (6)$$

The quadratic fit was calculated as follows:

$$WC = a_1 * C + a_2 + a_3 * C^2 \qquad (7)$$

with *WC* as water content, *C* as electrical conductivity, and a_0, a_1, and a_2 as coefficients.

The linear fit was used for the bryophyte species *Symbiezidium barbiflorum* and *Octoblepharum cocuiense*, the linear fit with exponential correction for *Sematophyllum subsimplex,* and the quadratic fit for *Leucobryum martianum* (Fig. S3).

The decision for these fits was based on the fits used in Weber et al. (2016) and on the maximum water contents reached during the calibration. In cases where the electrical conductivity values of field measurements were in a similar range as during calibration, we applied the fit of highest accuracy. If, however, values of field measurements largely exceeded those of calibration, we applied a quadratic fit or linear fit with exponential correction to avoid unrealistically high water content values in the extrapolated data range.

A calibration was conducted for 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. 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].

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 of the WCs reached during the laboratory measurements. We assume, that the maximum electrical conductivity achieved in the field equals the maximum WC achieved in the laboratory, due to water saturation of the samples during the laboratory measurement. Minimum electrical conductivity values reached in the field were assumed to correspond to air-dry samples, as we are confident that the samples dried out at least once during the dry season of the year. Accordingly, the water content (WC) was calculated as follows:

$$WC\ [\%\ DW] = \frac{(EC_i - EC_{min})}{(EC_{max} - EC_{min})} * (WC_{max} - WC_{min}), \qquad (4)$$

, with EC_i as electrical conductivity, EC_{min} as minimum electrical conductivity, EC_{max} as maximum electrical conductivity in the field, WC_{max} as the maximum WC in the laboratory, and WC_{min} as the minimum WC in the laboratory.

Generally, we observed the fits to have a high accuracy in the range of medium water contents, whereas at high and low water contents the accuracy tended to be lower (Fig. S53).

The quality of each fit was determined by calculating the RMSE of Pearson's R, comparing the predicted versus observed WC (*WCpred*, *WCobs*) with: (Table S1).

$$RMSE = \sqrt{\frac{\sum (WCobs - WCpred)^2}{N}} \qquad (85)$$

The measured electrical conductivity values showed short-time oscillations, which could be removed with a 30-minute smoothing algorithm (Fig. S4). Thus, for all calculations the 30-minute averages have been considered, 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)~~ species~~) were combined to obtain average values for each height. ~~As microclimatic conditions within one height level differed between samples, depending on their exact position and micromorphology, the average values reflect mean moisture conditions at the respective height levels.~~

~~2.5~~2.4 Meteorology

For the purpose of long-term monitoring, a set of~~The~~ meteorological parameters ~~has~~is being~~ve been~~ measured within the ATTO project since 2012. In our study we ~~utilized~~ used rainfall data collected 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) data assessed at 75 m height above the ground [µmol m^{-2} 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 ~~at 1-minute intervals~~ (Andreae et al., 2015).

For ~~the~~ 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. ~~The~~ R~~r~~ainfall is presented as accumulated values in millimeters per month, season, or year, which was calculated by an integration of 5-minute intervals. As there were gaps in the readings of the rain gauge, additional information from the ~~water content~~WC sensors was 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 rain gauge readings 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 ~~S3~~S2).

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.

T~~he t~~ime 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.

~~2.6~~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~~between~~ net photosynthesis (NP) ~~and~~ or dark respiration (DR) dominates the overall metabolic balance. Furthermore, high nighttime temperatures cause increased carbon losses due to high respiration rates, as indicatedpreviously shown for lichens (Lange et al., 1998, 2000).

To assess the potential physiological activity of bryophyte communities, the water and light conditions as major drivers of the metabolism need to bewere investigated in somewhat greater detail. The lower water compensation point (WCP$_l$) presents the minimum WC that allows physiological activitypositive net photosynthesis. For tropical species in lowlands atnear sea level in Panama, values in the range between ~ 30 and ~ 80225 % have been determined (Romero et al., 2006; (Wagner et al., 2013; Zotz et al., 1997, 2003) (Table S2S3). The water saturation point (WSP) presents the level of WC at which 95 % of the maximum NP rate is reached; at a higher water content a supersaturation may limit the gas diffusion and cause a decrease of NP. The WSP has been determined to range between ~ 349 and ~ 1 053 % for tropical bryophyte species (Romero et al., 2006; Wagner et al., 2013).

The lower light compensation point (LCP$_l$) represents the minimum light intensity that allows a positive photosynthesisprimary production; it ranges between ~ 53 and ~ 6912 µmol m^{-2} s^{-1} PPFD for bryophytes in African tropical lowland rain forests cryptogams (Lange et al., 2000; Romero et al., 2006; Wagner et al., 2013) (Lösch et al., 1994). At light intensities below the compensation point and water contentWCs above the WCP,l respiration rates are higher than NP rates, causing overall net respiration to occur takes placedominates the carbon balance. The light saturation point (LSP), where 95 % of the maximum NP rate are reached, was determined to range between ~110 and ~400 µmol m^{-2} s^{-1} PPFD (León-Vargas et al., 2006; Zotz et al., 1997).

With regard to temperature, a range for optimumal NP (T$_{opt}$; 95 % of maximum NP rate reached) and an upper compensation point, where NP equals DR, (TCP$_u$), can be defined. For tropical bryophytes, T$_{opt}$ ranges between 16.024 and 27.5 °C and the TCP$_u$ between 30.0 and 36.0 °C (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. 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).

Based on these literature dataand the 5-minute microclimate data, we calculated from 5-minute data grid the ranges of timespans of photosynthesis and respiration according to the following ruleswhen these key points were passed, because we don't likenot to miss short light flecks , by using just 30-minute averages (Frahm, 1990; Lösch et al., 1994; Wagner et al., 2013). A water contentWC above the compensation point allows NP if both light intensity and temperature are above the compensation point. If water contentsWCs 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 water contentsWCs, when samples are activated already but despite sufficient light intensities only net respiration can be proceededmeasured. As this span of water contentWCs 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 ~~we found assumed~~decided ~~that~~ 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.

~~2.7~~2.6 ~~Statistical~~ 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). ~~Statistical tests for normal distribution and variance homogeneity of data sets, as well as Mann-Whitney U tests were performed with the software OriginPro (Version 8.6; OriginLab Corporation, Northampton, Massachusetts, USA), the Kruskal-Wallis test with subsequent post-hoc test was performed with Statistica (Version 13.3; StatSoft GmbH, Hamburg, Germany).~~ 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 ~~(micro-) climatic~~ the WC, ~~and ecophysiological parameters~~ temperature, and light conditions experienced by~~of~~ the epiphytic bryophyte communities, as well as the above-canopy meteorological conditions, varied ~~depending on~~ 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 ~~than~~ as compared to the same time-span in the previous year (Fig. 1, Table S2~~1~~). The monthly mean values of ~~mesoclimatic ambient~~above-canopy PAR (~~ambient~~ PAR_{avg}) were rather stable throughout the years and did not differ ~~significantly (p = 0.633)~~ between the years 2015 and 2016, ranging between 315 and 570 µmol m^{-2} s^{-1} ~~PPFD~~ ~~in~~ during the daytime (Fig. 1, Table 1a). Within the canopy, the PAR_{avg} values at 1.5 m also showed only minor seasonal variation, whereas those at higher levels ~~had~~ revealed larger variations (Table S4). At 23 m height, PAR_{avg} values tended to be higher during the dry seasons. Comparing the two subsequent years, the annual mean values of the monthly PAR_{avg} ~~were significantly~~ tended to be higher at 1.5, 8, and 18 m, ~~whereas~~ but lower at 23 m ~~they were lower~~ in 2015 compared to 2016 ~~(each height p ≤ 0.001, Table 1a)~~. Over the course of the years, the monthly mean temperatures at all heights as well as ~~mesoclimatic ambient~~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 ~~mesoclimatic ambient~~temperatures measured above the canopy (Fig. 1, Table 1a, Fig. S6~~5~~). Overall, temperatures at all height levels were lower and more similar during the wet than the dry seasons. Maximum differences of monthly mean temperatures between the wet and the dry season were 5.0 °C at 23 m height, 3.0 °C at 1.5 m height, and 4.0 °C for mesoclimatic ambientabove-canopy values (Tab. S2, Tab. S4).

The monthly rain, RH, and water contentWCs of epiphytic bryophytes showed similar patterns over the course of the years. During the dry season 2015, it rained on 25 % of the days per month, while in the previous and subsequent years rain occurred at a higher frequency (58 % and 31 % of the days per month, respectively; Fig. 1, Table S3S2). Monthly rain amounts varied from 9 mm during the dry to 3410 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 monthly average of the above-canopy RH values were characterized by a similar behavior, with an increase from January to March 2016 and a subsequent decrease, while in the end of 2014 and the first half of 2015 the RH values showed minor fluctuations compared to those of the rain amounts. The lowest monthly average of the RH was detected during the dry season 2015 with 74 ± 15 %.

The WC values of epiphytic bryophyte communities at different height levels were the highest at 1.523 m, followed ofby those at 18 m. During the dry seasons, the WCs of mosses at 1.5 m tended to be the lowest, whereas during the wet seasons they were rather similar to the WCs of mosses at 8 m, whereas those of the liverworts at 8 m height had the lowest valuesand decreased towards 23 m and 18 m, being the lowest at 8 m height (Table Fig. 1). 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. Furthermore, the bryophytesliverworts at 8, and 18, and 23 m height showed particularly high WC values in November and December 2016, which might be caused by a previously required 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 %. In contrast, during the dry season the precipitation events were much rarer and smaller, there was hardly any occurrence of fog, and the RH values were regularly reached values below 60 % (Fig. 2, Fig. S5). The temperature and light conditions within and on top of the epiphytic bryophyte communities followed the mesoclimatic ambientabove-canopy climatic conditions, modified by the canopy shading.

The mesoclimatic ambientabove-canopy light intensity above the canopy was on averagetended to be higher in the dry season than as compared to the wet season (970 ± 650 vs. 740 ± 570 μmol m^{-2} s^{-1} PPFD) and the values showed stronger fluctuations. During both main seasons the average light intensity 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, with values at 23 m being lower than at 8 m or 18 m height (Fig. 2, Table 2).

The temperatures showed larger diel amplitudes in the dry compared to the wet season. Temperatures reflected a decreasing gradient from the canopy towards the understory and differences among heights were more pronounced during the dry season (Fig. 2, Table 2). At 23 m height, temperatures within the bryophyte communities were frequently higher than the ~~mesoclimatic ambient~~above-canopy values, and during the dry season even the seasonal average temperature ~~seasonal value~~ was 0.5°C higher, probably due to surface heating (Tab. S2).

During 2015 and 2016, rain occurred in the wet season on 81 and 87 % of the days and in the dry season on 25 and 31 % of the days, respectively. During the dry season the RH reached on average 87 ± 14 %, while in the wet season the average RH was 95 ± 9 % and frequently even full saturation was reached. Fog was recorded on 56 and 67 % of the days during the wet seasons of 2015 and 2016 and on 27 and 16 % of the days during the dry seasons, respectively (Fig. 2, Table 2).

The WC of the ~~bryophytes~~ mosses at 1.5 and 8 m and the liverworts at 18 m height responded consistently to rain events, while for the liverworts at 8~~, 18,~~ and 23 m height not in all cases an immediate response was observed. The ~~epiphytes~~ mosses at 1.5 m height had an ~~high~~ increased WC over several days ~~or even weeks~~ during the wet season, while in the dry season they had lower WC values. The bryophytes at the upper three heights showed a regular and pronounced nightly increase of WC~~, especially during the dry season~~ (Fig. 2, Fig. S5). Nightly fog might serve as an additional source of water, as the WC of the bryophyte communities increased upon fog events (Fig. S7).

3.1.3 Diel cycles ~~(~~in different seasons and years along ~~the~~a vertical gradient~~)~~

The diel cycles of ~~micrometeorological the water content~~WC, ~~and ecophysiological~~ temperature, and light conditions experienced by epiphytic bryophyte communitie~~sconditions~~ showed varying characteristics during the wet and the dry seasons (Fig. 3). The diel variability of light and temperature ~~experienced by the bryophytes~~ was larger in the canopy than in the understory, while ~~the~~ for ~~variation of the water content (~~WC~~)~~ of bryophytes the diel variability was the largest at the ~~lowest~~ two uppermost height levels. Comparing the seasons, the diel amplitudes of light, temperature, and RH were larger in the dry compared to the wet season, while for the WC of bryophytes the results did~~o~~ not present a clear pattern. The liverworts in the canopy tended to follow a higher amplitude of the WC during the dry season, while the mosses in the understory (at 1.5 m height) tended to show larger variations during the wet season.

The average daily ~~mesoclimatic ambient~~above-canopy light intensities (PAR_{avg}) were higher ~~during~~ in the dry than in the wet season, and also the PAR_{avg} on top of the epiphytic bryophytes at different height levels predominantly reached higher values during the dry season (Fig. 3). This mostly corresponds well with the daily maximum and amplitude values measured by the ~~mesoclimatic ambient~~above-canopy climate and the microclimatic sensors, as these mostly were also higher during the dry seasons. Exceptions from that were the lower ~~mesoclimatic ambient~~above-canopy values during the dry season 2015 and relatively low values at 8 m and 1.5 m height during the dry season 2016 (Table S5, S6, S7). ~~The variability and the diel amplitudes tended to be higher for the epiphytes in the canopy than for the organisms~~ ones ~~in the understory.~~

The ~~mesoclimatic ambient~~above-canopy temperatures showed larger diel amplitudes and higher values in the dry compared to the wet seasons (Fig. 3). Also mean daily maxima were higher with 33.5 ± 2.0 and 32.5 ± 2.0 °C during the dry compared to 29.0 ± 2.5 and 30.5 ± 2.0 °C reached during the wet seasons of 2015 and 2016, respectively. The microclimatic mean temperatures measured within the epiphytic bryophyte communities showed an increasing daily amplitude and increasing~~ly~~ ~~higher~~ maxim~~al~~um temperatures from the understory to the canopy. Daily maxima, minima, and amplitudes were larger in the dry than the wet seasons.

The mean RH values showed larger daily amplitudes in the dry compared to the wet seasons with particularly large amplitudes during the dry season 2015 (Fig. 3). Also the mean daily maxima of RH reached only 96 % in the dry season 2015, whereas in all other seasons (i.e., dry season 2016 and both wet seasons) values above 99 % were reached. The diel mean WC of epiphytic ~~bryophytes~~ liverworts was the highest at ~~1.5~~23 m and also daily maxima, minima, and amplitudes were the highest at this level. At 23 m height, also ~~At 1.5~~~~23 m height, t~~the daily amplitudes tended to be ~~were significantly~~ higher during the dry~~wet~~ compared to the wet~~dry~~ seasons, whereas for the mosses at the ~~higher~~ lowest height level~~s~~ the amplitude tended to be higher during the wet season~~, and at~~. For bryophyte communities at the other height levels the amplitudes during the different seasons were less clear. ~~. The WC of the epiphytic bryophytes at 8 and 18 m height were relatively constant in the year 2015, while values were more variable during the dry season 2016.~~

3.2 Potential physiological activity of bryophytes

~~In the tropical rain forest environment, the physiological activity of cryptogams, including bryophytes, is predominantly controlled by water and light, whereas the temperature plays a minor role (Lange et al., 2000; León-Vargas et al., 2006; Romero et al., 2006; Wagner et al., 2014).~~ While the availability of water determines the overall time of physiological activity, light ~~regulates between~~ is essential for net photosynthesis to occur ~~and dark respiration~~. Furthermore, ~~a~~ high nighttime temperatures cause~~s~~ increased carbon losses due to ~~high~~ increased respiration rates. Whereas overall light intensities at the upper three height levels were similar, with values mostly ranging between 0 and 100 µmol m^{-2} s^{-1} ~~PPFD~~ and maximum light intensities of 1,~~-~~500 (8 m), 1,~~-~~040 (18 m), and 950 µmol m^{-2} s^{-1} (23 m), intensities at 1.5 m height were extremely low, mostly reaching 0 – 10 µmol m^{-2} s^{-1} ~~PPFD~~, although maximum values of 1,~~-~~550 µmol m^{-2} s^{-1} ~~PPFD~~ were measured (Fig. 4). ~~The light intensities i~~In the understory (1.5 m) ~~reached~~ the lower light compensation point~~s~~ (LCP_l), ranging between 3 and 12 µmol m^{-2} s^{-1} ~~described in the literature (Wagner et al., 2013)~~ (Lösch et al., 1994), was only reached during 2 – 15~~0 – 8~~ % of the reported time~~, suggesting that during most times respiration exceeded photosynthesis~~. ~~,~~ whereas a~~A~~t higher canopy height levels~~,~~ the bryophytes reached these values during 29 – 47~~4 – 45~~ % of the time (Table 3). ~~Light saturation points (LSP),~~

which have been reported to range between 110 and 400 µmol m^{-2} s^{-1} PPFD (León-Vargas et al., 2006; Zotz et al., 1997), were hardly ever reached in the understory and only rarely in the canopy. Light intensities above the saturation point were mostly reached when sunspots briefly reached the bryophytes.

The microclimatic temperatures were fairly similar throughout at different height levels within the canopy, mainly rangeding between 23.0 and 33.0 °C (Fig. 4). In tropical lowland regions, the optimum temperatures for bryophytes (T_{opt}) range between 254.0 and 27.05 °C (Frahm, 1990; Wagner et al., 2013). In our studies this optimum was matched during 6 6 – 32 51 % of the time (Table 3). The upper temperature compensation point (TCP_u) of 30.0 – 36.0 °C (Wagner et al., 2013), above which respiration exceeds photosynthesis, was surpassed during 0 – 11 % of the time in the understory and 0 – 17 % in the upper three canopy levels. Overall, the highest temperatures were reached, when the bryophytes were relatively dry (Fig. S98).

The water contentWC of bryophytes differed along the vertical profile, with substantially higher values reached in the understory canopy (18 and 23 m) than at in the upper threeunderstory height levels (1.5 and 8 m), where a stepwise increase in water contents was observed. The lower water compensation point (WCP_l), ranging between 30 and 225 80 % according to the literature (Romero et al., 2006; Wagner et al., 2013), was reached during 0 – 88 % of the time in by mosses (1.5 and 8 m), during 2 – 33 % by liverworts (8 m) in the understory, and during 2 – 100 % of the time by liverworts in the canopy (18 and 23 m;) and 0 – 100 % at the upper three height levels (Fig. 4; Table 3). The water saturation point (WSP) was reached during 1 – 22 % of the time by understory bryophytes, while at the upper three canopy levels water saturation was never reached.

Recapitulating our findings about the compensation points of water, light, and temperature, one can make rough estimates of the potential time fractions of physiological activity, i.e., NP and DR, of the bryophytes at different heights (Table 3). As the upper lower end of the WCP_l range is reached during 100% of the time at all height levels, one can expect bryophytes to be active during major fractions of their lifetime, although this fraction potentially is larger at lower heights of growth. Also the microclimatic temperatures are mostly favorable and only rarely above the upper compensation points at all canopy height levels, thus in theory mostly facilitating NP. Light intensities, however, vary widely with height and are decisive for the overall theoretical duration of NP taking place. Considering the lower end of the range of the LCP_l (i.e., 225 µmol m^{-2} s^{-1} PPFD) and the WCP_l (i.e., 30 %), and the upper end of the $T_{NP=DR}CP_u$ (i.e., 36.0 °C), the NP is reached during 47 – 59 % of the time at higher canopy levels, while in the understory (1.5 m) it is only achieved during 8 % of the time. Assuming the upper end of the LCP_l (69 µmol m^{-2} s^{-1} PPFD) and the WCP_l (225 80 %), and the lower end of $T_{NP=DR}CP_u$ (i.e., 30.0 °C), NP would not occur at any of the different height levels. The time fractions representing theoretical duration of DR are similar at the three canopy levels, ranging between 0 – 43 %, whereas in the understory DR occurs during 50 – 96 % of the time (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 over the course of more than two years. ~~However, these measurements of the bryophyte communities WC in several height levels over the period of more than two years allows the monitoring of the moisture status of the epiphytic bryophytes.~~ In previous studies, such data have only been assessed only over short time-spans ~~dealing with the moisture status of bryophytes or other epiphytes were performed for a small time fraction~~ of hours or days (Romero et al., 2006; Wagner et al., 2013; Zotz et al., 1997).

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

Over the course of two years, the ~~mesoclimatic ambient~~above-canopy average monthly light conditions (PARavg) were rather stable. In previous studies, increased biomass burning activities during El Niño in 2015 were reported to cause an increase of smoke and soot particles in the atmosphere (Saturno et al., 2017), and our data also suggest a slight reduction of monthly PAR_{max} during the dry season 2015 (Table ~~S3~~S2). 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, ~~and~~ cushion orientation, and shading. ~~, as t~~The sensors ~~were installed with the following orientations:~~ at 1.5 and 8 m were installed vertically along the trunk ~~vertically along the trunk~~, ~~at~~ 18 m height they were placed on the upper side of a slightly sloped branch ~~at 18 m at the upper side of a slightly sloped branch~~, and at 23 m they were positioned on the upper side of a vertical branch ~~at 23 m,~~. ~~at the upper side of a vertical branch~~. As the light sensors ~~on top of the bryophytes~~ at 23 m height were located within the canopy, newly growing leaves may have periodically shaded the organisms, which~~. This~~ ~~can~~~~could~~may explain the lower monthly PAR_{avg} values ~~in the canopy~~at this height level compared to the values at the lower ~~height~~ levels.

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. ~~The diel amplitudes of PAR_{avg} were larger in the dry than the wet season and larger in the canopy than the understory.~~ 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 during 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 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 microclimatic temperatures measured within the bryophyte ~~cushion~~communities followed the ~~mesoclimatic ambient~~above-canopy temperature at all height levels, with a mostly~~n~~ increasing gradient from the understory towards the canopy, probably caused by a reduced shading effect towards the canopy. At the uppermost height level, mean temperatures within bryophyte communities often were even higher than the mean ~~mesoclimatic am-bient~~above-canopy temperatures. ~~This pattern was mainly observed during the dry seasons, when canopy shading only played a minor role and reduced wind velocity resulted in a stronger surface heating effect.~~ 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 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 ~~for~~ 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 diurnal and seasonal temperatures were the most stable in the understory, whereas the largest variations were observed in the canopy. The daily amplitude of the temperature was about twice as large in the canopy as compared to the understory (Tab. S6). This could be ~~expected~~ caused by the~~due to~~ exposure to ~~the~~ strong solar radiation and higher wind velocity in the canopy compared to the sheltered understory (Kruijt et al., 2000).

The two consecutive years 2015 and 2016 were by no means identical, as rainfall amounts and relative air humidity values were considerably higher between October 2014 and February 2015 as compared to the following year. The dry season of 2015/2016 was affected by an El Niño event, causing air humidity and WC of bryophytes to be ~~significantly~~substantially ~~-~~lower compared to the previous dry season (Fig. 1, Table 1). ~~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 rein-stallation of some sensors, which previously had fallen out of the moss cushions. Sensor displacement or complete removal from the bryophyte samplescushions 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 cushion sample properties. This variability of data, depending on the exact placement of the sensors, illustrates that calculated WC contents could only be considered as approximate values.~~

As expected, the response of the ~~water content~~WCs of bryophytes upon rain, fog, and high RH differed between seasons. During the wet season, the RH and the ~~bryophyte~~ WC of the moss communities at 1.5 and 8 m and the liverwort communities at 23 m ~~was significantly~~ tended to be higher as compared to the dry season (Table 2~~3~~), when the RH values showed ~~a stronger decrease~~lower values ~~in~~ during the daytime. During the wet season, the frequency of rain was ~~much~~ higher, and thus affected especially the moss communities ~~bryophytes in the understory~~at the lower levels (1.5 and 8 m;~~)~~ ~~were often still an increased WCwetnot completely dry when the next rain event started, while the WC of the liverworts bryophytes in the canopy had already dried outdecreased to the minimal level frequently reached during daytime (~~Fig. S5~~6~~a).

Furthermore, the angle of the stem or branch colonized by the investigated bryophytes played a crucial role for rainwater absorption and the subsequent drying process ~~(Table 2Fig. S2)~~. 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., 2018). At 8 m height, the investigated bryophytes were exposed to the west, and thus were only sometimes directly influenced by precipitation~~, as in most cases, due to the predominant wind directions, north-, east-, and south-oriented tree fractions received the largest precipitation amounts~~. ~~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., 2018). In contrast to that, the bryophytes~~Also at ~~18~~ 23 m height the bryophytes did not always show~~ed~~ a clear response to precipitation events~~, even if~~although they ~~we~~are oriented horizontally on a branch (Fig. 2, Fig. S5~~6~~). ~~Here, the bryophyte cushions were exposed to the south, which is more frequently influenced by rain events. Thus, the shift of the main wind direction from northeasterly to southeasterly might explain the fact that the bryophytes at 18 and 23 m height responded more strongly to rain events in the dry season than they did in the wet season. Moreover~~It can be expected that, besides the dominating wind direction, also the tree foliation and epiphytic vascular plants might shield the sensors from direct precipitation during the wet season.

During the dry season, the drying of the samples located in the canopy occurred quite rapidly after rain. 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 cause no complete water saturation of the bryophytes. Consequently, the organisms dry much quicker than after a strong rain event that fully saturates the community~~facilitates fast drying of the cryptogams inhabiting the canopy~~. Besides ~~the~~ solar radiation, probably also the higher wind velocities accelerated the desiccation of the epiphytic cryptogams in the canopy (Oliver, 1971). The diel ~~mesoclimatic ambient~~above-canopy RH amplitudes were larger and reached lower values during the dry season, thus also promoting quicker drying of samples.

~~Furthermore~~In a rainforest environment, condensation and stemflow water need to be considered as ~~a~~ 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 ~~shown~~ estimated that in tropical forests 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 ~~the~~ values of 68 and 75 mm in the years 2015 and 2016 at the ATTO site. The WC of bryophytes in the understory showed a high variability during the wet season, indicating that large amounts of water were taken up during prolonged rain events, which were subsequently lost again in a stepwise manner, with bryophytes often staying wet and active over long time spans (Fig. 2, Fig. S5). The high WC ~~particularly large water holding capacity~~ of the ~~organisms~~ bryophyte samples in the ~~understory~~ canopy might~~ay~~ be partly ~~also be~~ explained by the different water holding capacity of different bryophyte species ~~growing (and measured) in the understory~~ and the canopy~~, which are especially as understory species of lichen and bryophytes are known to be adapted to long-term water storage~~ (Lakatos et al., 2006; Romero et al., 2006; Williams and Flanagan, 1996). The species dominating the measurements in the canopy (23, 18, and 8 m) was a liverwort, while in the understory (1.5 and 8 m) moss species were dominating the measurements. ~~Thus, the difference of the bryophytes WC in the different height is not only caused by environmental factors as water availability, wind, radiation, and exposition, but furthermore, it represents the variability among species.~~

~~However, these measurements of the bryophyte communities WC in several height levels over the period of more than two years allows the monitoring of the moisture status of the epiphytic bryophytes. In previous studies dealing with the moisture status of bryophytes or other epiphytes were performed for a small time fraction of hours or days (Romero et al., 2006; Wagner et al., 2013; Zotz et al., 1997).~~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.

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 ~~their~~ morphological and physiological features. Apart from the long-term adaptation of the metabolic properties, the performance of species under differing microenvironmental conditions can also be modulated by acclimation processes (intraspecific variability), as, e.g., shown for bryophytes and lichens (Cornelissen et al., 2007; Pardow et al., 2010). These two aspects help to understand the occurrence of bryophytes under widely varying microclimatic conditions within the canopy. It was recently demonstrated that a prediction of the physiological activity patterns of cryptogamic organisms and communities was possible ~~alone~~ on the basis of climatic conditions alone (Raggio et al., 2017).

During our study, we also observed bryophyte taxa to vary depending on the microenvironmental conditions. Whereas at the stem bases close to the ground the moss species *Sematophyllum subsimplex*, *Octoblepharum cocuiense*, and *Leucobryum martianum* were dominating, ~~, *Octoblepharum cocuiense* and~~ the liverwort *Symbiezidium barbiflorum* wa~~ere~~s the main species occurring at higher levels along the tree stem~~at the ATTO site, obviously in close adaption to the specific locations~~. 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).

~~Epiphytic organisms are known to be adapted to environmental light conditions, with LCP_l and LSP being lower under low-light conditions in the understory as compared to the canopy, as experienced for epiphytic lichens in French Guiana (Lakatos et al., 2006). It can be expected the light compensation points of organism to be adapted to the environmental conditions, as experienced for epiphytic lichens in French Guiana (Lakatos et al., 2006).~~ 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, the organisms need to react rapidly and efficiently to changing light conditions to reach overall positive net photosynthesis rates, and it has been reported that understory mosses and lichens indeed 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 are also known to have lower LCP_l values under low-light conditions in the understory compared to the canopy, as documented for epiphytic lichens in French Guiana (Lakatos et al., 2006). ~~As reference we included the ranges of LCP_l given by Romero et al. (2006), who reported 5 µmol m^{-2} s^{-1} PPFD as the lowest light compensation point, which was reached during 45 % of the time in the canopy and 8 % of the time in the understory (Fig. 4, Table 3). In such cases, the organisms need a very rapidly and efficiently operating photosystem to reach overall positive net photosynthesis rates, and it has been reported that understory mosses indeed show higher rates of net photosynthesis than canopy species (Kangas et al., 2014; Lakatos et al., 2006; Wagner et al., 2013). However, for other habitats, light compensation points as low as 1 µmol m^{-2} s^{-1} PPFD have been defined for lichens (Green et al., 1991), and thus we could imagine that the understory organisms at the ATTO site exhibit similarly low LCP_l values.~~

The temperature regulates the velocity of metabolic processes, hence~~. Whereas~~ it has a strong impact on the respiration, while the photosynthetic light reaction~~s are~~is by far less sensitive ~~to temperature~~ (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~~. Thus~~, positive net photosynthesis ~~rates~~ may still be reached at higher temperatures~~ in the light~~, ~~as long as~~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). Furthermore, it was indicated that the temperature might not be a limitation factor for growth of bryophytes, as the species are well adapted to the prevailing environmental conditions (Wagner et al., 2013).

The optimum temperatures for net photosynthesis (T_{opt}) range from 25.0 to 27.5 °C for tropical bryophytes (Wagner et al., 2013), and these values were reached during 6 to 32 % of the time at all four height levels with no major differences among them. The upper temperature compensation point (T_{CPu}) between 30.0 and 36.0 °C (Wagner et al., 2013) was only rarely reached during our study (i.e., up to 17 % of the time). TheIn 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 does did not seem to play a relevant role asbe a limiting factor for the physiological activity of epiphytic bryophytes in this environment (Fig. S8). Similarly, Wagner and coauthors (Wagner et al., 2013) stated thatFurthermore, it was indicated that the temperature mightlikely was not be a limitingation factor for NP and growth of the bryophytes investigated by them in a lowland and highland rainforest in Panama, as the species are well adapted to the prevailing environmental conditions (Wagner et al., 2013).

The WC of bryophytes has been shown to be higher in the understory canopy than in the canopyunderstory. In the understory, the WCP_l was reached between 25 1 and 100 36 % of the time, depending on the literature value being considered, whereas at 18 and 23 m it was reached during ~3 – 100 % and the WSP was reached during 1 – 22 % of the time. In the understory, the WC of cryptogams seems to be predominantly regulated by rain events and the vegetation reduces the evaporation by its shadowing effect. An increased RH slows down the drying process, causing the samples to dry over a longer time-range, especially during the wet season (Fig. 2). In the canopy, the samples stayed relatively homogeneously wet over long time spans. 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 on top of nearly vertical stems, they probably could store the water over longer times.

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 bryophyte WC could increase upon fog (Fig. S7),

In the canopy, the WCP_l was reached between 0 to 100 % of the time, whereas the WSP was almost never reached.

Investigating six tropical bryophyte species Zotz et al. (1997) pointed out that the WC of bryophytes varied between 310 and 2 000 %, depending on the species. During their investigation in September/October 1993, the WC of the bryophyte species *Leucobryum antillarum* varied between 1 200 and 1 400 %, while in our investigation the WC of *Leucobryum martianum* ranged between 200 and 1 950 % during the same time of the year. Thus, both ranges of WC are comparable and the larger range recorded in our study might result from the longer observation period (September 2015, 2016, October 2014, 2015, and 2016). which has also been shown in some

Furthermore, water from fog might trigger a physiological activity of bryophytes, other studies (León-Vargas et al., 2006). , and aAlso 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, ~~they~~ Lakatos and coauthors showed that lichens benefit from dew formation on the thallus surface during noon, and we can assume that similar processes 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.

~~In the understory, the WC of cryptogams seems to be predominantly regulated by rain events~~ and ~~. Additionally, the vegetation reduces the evaporation by its shadowing effect~~, ~~whereas in the canopy~~ , ~~rain events,~~ fog , ~~, and condensation seem to be equally important water sources for cryptogams. Our data have shown that in the understory the bryophytes stay wet for most of the time, and consequently they might be more sensitive to drought than canopy species~~ , ~~which has also been observed by Pardow and Lakatos (2013)(Pardow and Lakatos, 2013).~~

~~As bryophytes are poikilohydric organisms, water availability controls their overall physiological activity, while light regulates the photosynthetic activity in an active organism state. Temperatures largely affect respiration of the organisms, whereas photosynthesis rates are affected to a minor extent (Green and Proctor, 2016; Lange et al., 1998; Weber et al., 2012). In the understory, the major limiting factor for photosynthesis was light, as during most of the day its intensity was very low, i.e., during 92 % of the time light intensity was below the potential~~ $\sim\sim LCP_l$ ~~of 5 µmol~~ $\sim\sim m^{-2} s^{-1}$ ~~PPFD (Table 3). Combining light, temperature, and water compensation points, the results suggest that understory bryophytes perform NP during 0 – 8 % and DR during 50 – 96 % of the time. It has been shown that understory organisms are adapted to low light conditions by rather high photosynthesis and low respiration rates (Pardow and Lakatos, 2013), which would facilitate their existence under the given environmental conditions. In the canopy, one may expect water to represent the limiting factor, as bryophytes were frequently exposed to higher light intensities and warmer temperatures, but according to~~ $\sim\sim WCP_l$ ~~ranging between 30 and 225 %, bryophytes at the upper three height levels perform positive NP during 0 – 59 % and DR during 0 – 43 % of the time. Generally, lower WCP and LCP contribute to larger rates of NP, whereas high compensation points cause respiration and inactivity. The adaption of the organisms to the environmental conditions is the crucial point of survival in this environment. All these time ranges of metabolically activity are only rough estimates, which predominantly depend on the actual compensation points being influenced by inter- and intraspecific variation.~~

~~There are also some differences between groups, as, e.g., lichens tend to perform photosynthesis at lower water contents 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, while inside one division also the interspecific variability can be rather huge. The wide ranges of potential activity and the scarcity of literature data illustrate the necessity of~~ $\sim\sim CO_2$ ~~gas exchange measurements to assess the actual diel and seasonal physiological activity and productivity of rainforest cryptogams under varying environmental conditions.~~

Based on our measurements combined with the compensation points of water, light, and temperature, one can make rough estimates of the potential time of NP and DR for bryophytes at the different height levels (Table 3). Whereas the lower end of the WCP range (30 % DW) was reached during 100 % of the time by the liverworts at the upper two height levels, the liverworts at 8 m reached this value only during 33 % of the time, and the mosses at 1.5 and 8 m height reached it only during 36 and 88 % of the time, respectively. For the LCP_l an even more critical pattern was observed, as the data suggest that it was reached only during 2 % of the time by communities at the ground level, whereas those at higher levels reached it during ~30 – 40 % of the time. In contrast to these factors, the temperature was only rarely limiting and there were no major differences between the height levels. Combining the ranges of the environmental factors needed for NP and DR to occur, our data suggested that NP and DR at the upper two height levels occurred during ~30 – 60 % and ~30 – 50 % of the time, respectively, thus being in a reasonable range. At the lower levels, however, the durations of NP and DR were relatively short and the results for the ground level suggested that NP occurred only during ~5% and DR during~10 – 25% of the time. These results appear highly unrealistic and thus we expect the LCP_l and the WCP at the lower levels and particularly at the ground level to be lower than the values that have been published up to now. For other habitats, light compensation points 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.

In the environment studied, the adaption 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, while 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 ~~water content~~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. IWhile in the understory the bryophyte water contentWCs vary widely between seasonsis mostly relatively low, but stays high for a longer time after intense rains. In contrast to that, the water content of the bryophytes at higher levels remains high and at similar values over most of the time, probably caused by the bryophyte morphology and also their growth habitat on top of a vertical stem and the organisms may stay wet on an increased over several days or even weeks during the wet season, those in the canopy are exposed to frequent wetting and drying cycles, even by the nightly increase of the RH. The light intensity during periods of physiological activity mainly determines whether NP takes placedominates or carbon is lost by dominating respiration. As the temperature shows only minor spatial, diel, and seasonal variation, it is onlymight 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 biogeochemical cycling in tropical habitats. However, tThe 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.local database at the Max Planck Institute for Chemistry and unrestricted access is provided upon request.

Supplement link

Author contribution

BW, CP, and NL designed the measurement setup. NL, CGGB, SB, 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 deviation (± SD)~~, and statistical significance~~ of mean daytime photosynthetically active radiation (PAR_{avg}), daily maxima of photosynthetically active radiation (PAR_{max}), temperature, ~~relative humidity (RH),~~ and water contents (WC) of bryophytes at the four~~ the~~ height levels ~~and of above-canopyambient conditions~~ 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 5-minute intervals, except for PAR_{max}, where the daily maximum values ~~has been~~were considered. Due to data gaps in the measured rain~~ data~~ (shown in brackets) values were also extrapolated from existing data as described in methods section (values behind ~~data in~~the brackets).~~ Due to absence of normal distribution and variance homogeneity, a non-parametric Mann-Whitney U test was performed to compare values obtained for the two years.~~

(a)

Height [m]	2015 Mean	2015 ± SD	2016 Mean	2016 ± SD
PAR_{avg} daytime[µmol m^{-2} s^{-1} ~~PPFD~~]				
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} ~~PPFD~~]				
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 [%]				
~~above-canopy (RH) RH,~~	~~86~~	~~15~~	~~90~~	~~13~~
23, Liverwort	27~~133~~	42~~41~~	116~~122~~	44~~42~~
18, Liverwort	107~~112~~	40~~38~~	170~~178~~	172~~179~~
8, Liverwort	25~~26~~	7~~7~~	67~~71~~	119~~124~~
8, Moss	55~~35~~	24~~14~~	57~~36~~	38~~23~~
1.5 Moss	41~~33~~	50~~41~~	31~~25~~	35~~28~~

(b)

Parameter	2015 Sum	2016 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 different parameters, photosynthetically active radiation (PAR_{avg}), daily maximum of photosynthetically active radiation (PAR_{max}), temperature, and above-canopy relative humidity/water content (WC) of bryophytes determined at different height levels and above the canopy. Mean values for the respective seasons were calculated from 5-minute intervals of the years 2015 and 2016, ex~~pec~~cept for PARmax, where the daily maximum values ~~has been~~were considered.

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	± SD	Mean	± SD
Wet season								
above-canopy	738	566	2086	515	25.6	2.5	143	36
23 Liverwort	30	3	248	194	25.3	2.0	125	33
18 Liverwort	39	12	282	175	25.2	1.9	113	37
8 Liverwort	31	26	144		24.9	1.1	31	10
8 Moss							64	29
1.5 Moss	4	15	114	224	24.9	1.0	60	50
Transitional season Wet-Dry								
above-canopy	861	649	2227	182	25.8	3.0	143	57
23 Liverwort	41	72	414	252	25.7	2.8	128	41
18 Liverwort	44	54	351	123	25.4	2.3	127	20
8 Liverwort	66	88	165	218	24.9	1.4	25	5
8 Moss							54	21
1.5 Moss	2	12	61	102	24.6	1.1	24	15
Dry season								
above-canopy	973	647	2100	609	26.7	3.4	119	52
23 Liverwort	55	9	503	231	27.2	3.5	122	52
18 Liverwort	41	13	412	190	26.5	2.9	107	52
8 Liverwort	23	16	295	268	26.0	2.1	32	28
8 Moss							51	33
1.5 Moss	6	25	209	299	25.5	1.7	23	20
Transitional season Dry-Wet								
above-canopy	785	617	1988	509	26.5	3.3	141	67
23 Liverwort	55	91	530	297	27.2	3.7	130	48
18 Liverwort	37	28	185	109	26.6	3.0	137	75
8 Liverwort	21	47	269	178	26.3	2.5	61	49
8 Moss							56	24
1.5 Moss	4	20	107	113	26.0	2.1	35	33

Table 2: Seasonal mean values, standard deviation (± SD), and statistically significant difference between seasons for the parameters photosynthetically active radiation (PAR_{avg}), daily maximum of photosynthetically active radiation (PAR_{max}), temperature, and above-canopyambient relative humidity/water content (WC). Values measured as above-canopyambient conditions and within/on top of bryophytes at four height levels. Mean values for the respective seasons were calculated from 5-minute intervals of the years 2015 and 2016, expect for the PAR_{max}, where the daily maximal value have been considered. Due to the absence of normal distribution and variance homogeneity, a non-parametric Kruskal-Wallis test with post hoc test was performed to compare values obtained forthe different seasons. The statistical comparison among height levels for the different seasons is shown in Table S5.

-	PAR_{avg} daytime [µmol m^{-2} s^{-1} PPFD]			PAR_{max} [µmol m^{-2} s^{-1} PPFD]			Temperature [°C]			WC; above-canopy RH		
Season	Mean	± SD	sig.	Mean	± SD	sig.	Mean	±	sig.	Mean	± SD	sig.
above-canopy												
Wet	738	566	a	2086	515	a	25.6	2.5	ab	94	9	a
Trans Wet-Dry	861	649	a	2227	182	a	25.8	3.0	ab	91	11	b
Dry	973	647	a	2100	609	a	26.7	3.4	bc	87	14	c
Trans Dry-Wet	785	617	a	1988	509	b	26.5	3.3	ca	85	15	d
Statistical test, p		1.000			≤ 0.001			≤ 0.001			≤ 0.001	
23 m	-	-	-	-	-	-	-	-	-	-	-	-
Wet	30	3	a	248	194	a	25.3	2.0	a	143	36	
Trans Wet-Dry	41	72	a	414	252	b	25.7	2.8	b	143	57	
Dry	55	9	a	503	231	c	27.2	3.5	c	119	52	
Trans Dry-Wet	55	91	a	530	297	c	27.2	3.7	d	141	67	
Statistical test, p		1.000			≤ 0.001			≤ 0.001				
18 m	-	-	-	-	-	-	-	-	-	-	-	-
Wet	39	12	a	282	175	a	25.2	1.9	a	110	37	
Trans Wet-Dry	44	54	a	351	123	b	25.4	2.3	b	133	20	
Dry	41	13	a	412	190	b	26.5	2.9	c	152	121	
Trans Dry-Wet	37	28	a	185	109	c	26.6	3.0	d	202	159	
Statistical test, p		1.000			≤ 0.001			≤ 0.001				
8 m Liverwort	-	-	-	-	-	-	-	-	-	-	-	-
Wet	31	26	a	144	194	a	24.9	1.1	a	32	11	
Trans Wet-Dry	66	88	a	165	218	a	24.9	1.4	ab	26	6	
Dry	23	16	a	295	268	b	26.0	2.1	bc	56	88	
Trans Dry-Wet	21	47	a	269	178	b	26.3	2.5	cd	72	100	
Statistical test, p		1.000			≤ 0.001			≤ 0.001				
8 m Moss	-	-	-	-	-	-	-	-	-	-	-	-
Wet										41	21	
Trans Wet-Dry										38	15	
Dry										30	23	
Trans Dry-Wet										42	23	
1.5 m	-	-	-	-	-	-	-	-	-	-	-	-
Wet	4	15	a	114	224	a	24.9	1.0	a	48	44	
Trans Wet-Dry	2	12	a	61	102	a	24.6	1.1	b	9	12	
Dry	6	25	a	209	299	b	25.5	1.7	c	13	11	

~~Trans Dry–Wet~~	4	~~20~~	~~a~~	~~107~~	~~113~~	~~b~~	~~26.0~~	~~2.1~~	~~d~~	~~27~~	~~34~~
~~Statistical test, p~~		~~1.000~~			~~≤ 0.001~~			~~≤ 0.001~~			

Table 3: The potential time ranges [%], during which the epiphytic bryophytes reached the lower compensation and saturation points of light (PARLCP$_l$), the optimal temperature for net photosynthesis (T_{opt}), the upper compensation points for temperature (TCP$_u$), and the lower compensation and saturation points of for water content (WCP). The conditions at which the compensation points were reached are listed, and the potential time ranges, during which NP and DR might occur were listed occurs (see methods section for details on calculation of NP and DR).) Values are given for the different height levels and bryophyte divisions (M=moss, L=liverwort). Five-minute averages of measurements during the entire measurement period from October 2014 to December 2016 were considered. The ranges of the compensation points (CP), saturation (SP) point and optimal ranges (opt) were reported in Frahm (1990), Zotz et al. (1997), Leon-Vargas et al. (2006), Romero et al. (2006), Lösch (1994) and Wagner et al. (2013) (see Table S2S3).

Height	Time when cardinal points are reached [%]						
Height[m]	**LCP$_l$** 5-693-12 µmol m^{-2} s^{-1}	**T_{opt}** 245.0-27.30 ° C	**TCP$_u$** 30.0-36.0 ° C	**WCP$_l$** 30-80225 % DW	**Conditions WSP** for NP and DR LCP$_l$/TCP$_{NP=DR}$/WCP34 % -	**NP** WC > WCP$_l$ & & T < TCP$_u$	**DR** WC > WCP$_l$ & PAR < LCP$_l$ or WC > WCP$_l$ & T > TCP$_u$
[m]	**Time fraction when cardinal points are reached [% of time]**				**µmol m^{-2} s^{-1}/°C/%DW**	**Time fraction when cardinal points are reached [% of time]**	
23 L	36-458-43	6-466-30	0-161-16	291-1000-	3-12/30-36/30-800	28-58350-55	40-47480-43
18 L	39-476-45	6-516-32	0-130-13	479-1000-	3-12/30-36/30-800	27-59320-59	30-33340-41
8 L	29-404-37	13-2913-29	0-170-17	2-336-400-	3-12/30-36/30-800	1-2330-47	3-1620-40
8 M				3-650-88	3-12/30-36/30-80	5-4633	9-3024
1.5 M	2-150-8	14-3014-30	0-110-11	8-29251-36-	3-12/30-36/30-801-22	0-650-8	10-261950-96

Figures

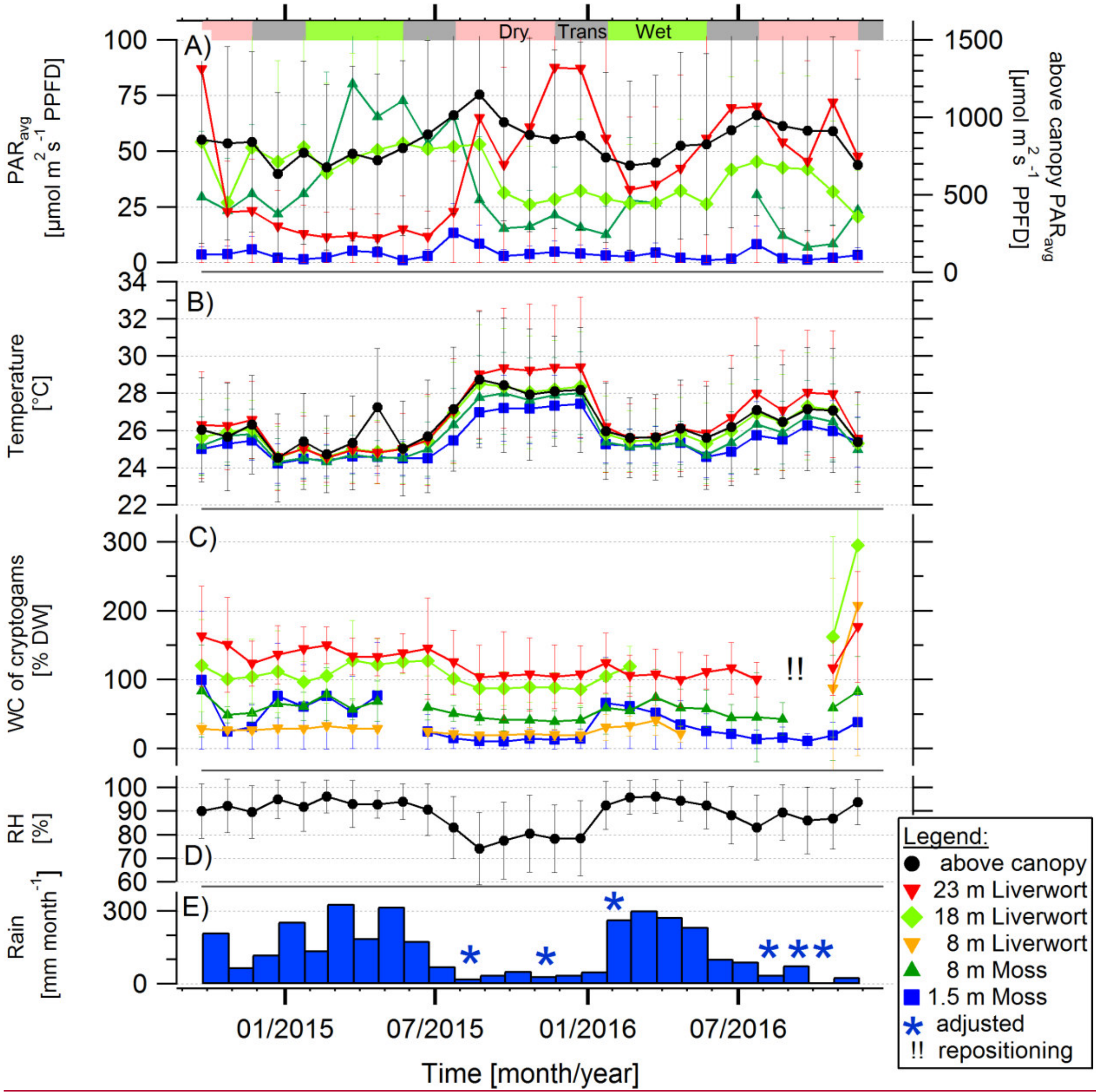


Figure 1: Water content (WC), ~~Ecophysiological~~temperature, and light conditions experienced by ~~of~~ bryophyte communitie~~s, micrometeorological~~, and ~~ambient~~ above-canopy meteorological conditions ~~experienced by epiphytic bryophytes~~ in the Amazonian rain forest. The ~~ecophysiological and~~ micrometeorological parameters on top/within epiphytic the cryptogamic communities represent monthly mean values ± SD of (A) average by day (06:00 – 18:00 LT) of photosynthetically active radiation (PAR_{avg}) on top, (B) temperature within, and (C) ~~water~~

contentWC of cryptogamic communities. The above-canopyambient meteorological parameters comprise (A) the monthly mean value of the average by day (06:00 – 18:00 LT) of above-canopyambient photosynthetically active radiation (PAR_{avg} at 75 m), (B) monthly mean value of above-canopy ambient temperature (at 26 m), (D) monthly mean value of relative air humidity (RH at 26 m height), and (E) monthly amount of precipitation (rain). Data of replicate sensors installed within communities at the same height level as 30-minute averages were pooled, while above-canopy ambient 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 S32 and S4.

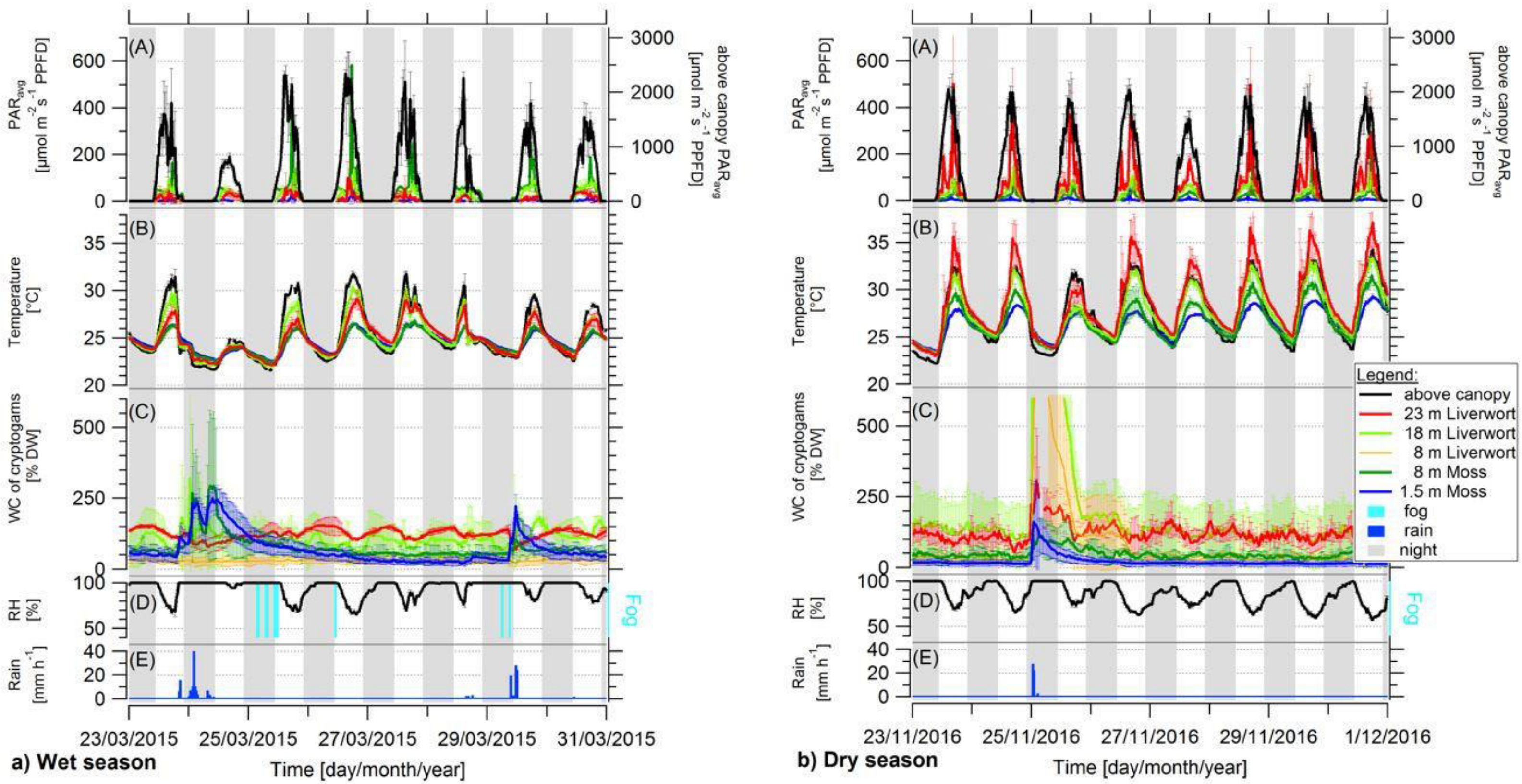


Figure 2: Representative periods during the wet and dry season under average conditions, showing~~-~~ water content (WC), temperature, and light condition (PAR_{avg}) of bryophytes, and above-canopy ~~ecophysiological, micrometeorological, and ambient~~ meteorological conditions ~~experienced by epiphytic cryptogamic communities~~ in the Amazonian rain forest. Shown are 8-day periods during (a) the wet season 2015 and (b) the dry season 2016. ~~Ecophysiological and~~The micrometeorological parameters on top/within epiphytic cryptogamic communities represent (A) the photosynthetically active radiation (PAR_{avg}) on top, (B) the temperature within, and (C) the ~~water content~~WC of cryptogamic communities. The above-canopy~~ambient~~ meteorological parameters comprise (A) above-canopy~~ambient~~ photosynthetically active radiation (PAR_{avg} at 75 m), (B) above-canopy~~ambient~~ temperature (at 26 m), (D) relative air humidity (RH at 26 m height), presence of fog events~~ (turquoise bars)~~, and (E) ~~precipitation (~~rain~~)~~. 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-canopyambient parameters were measured with one sensor each. The night time is shaded in grey (06:00 – 18:00 LT).

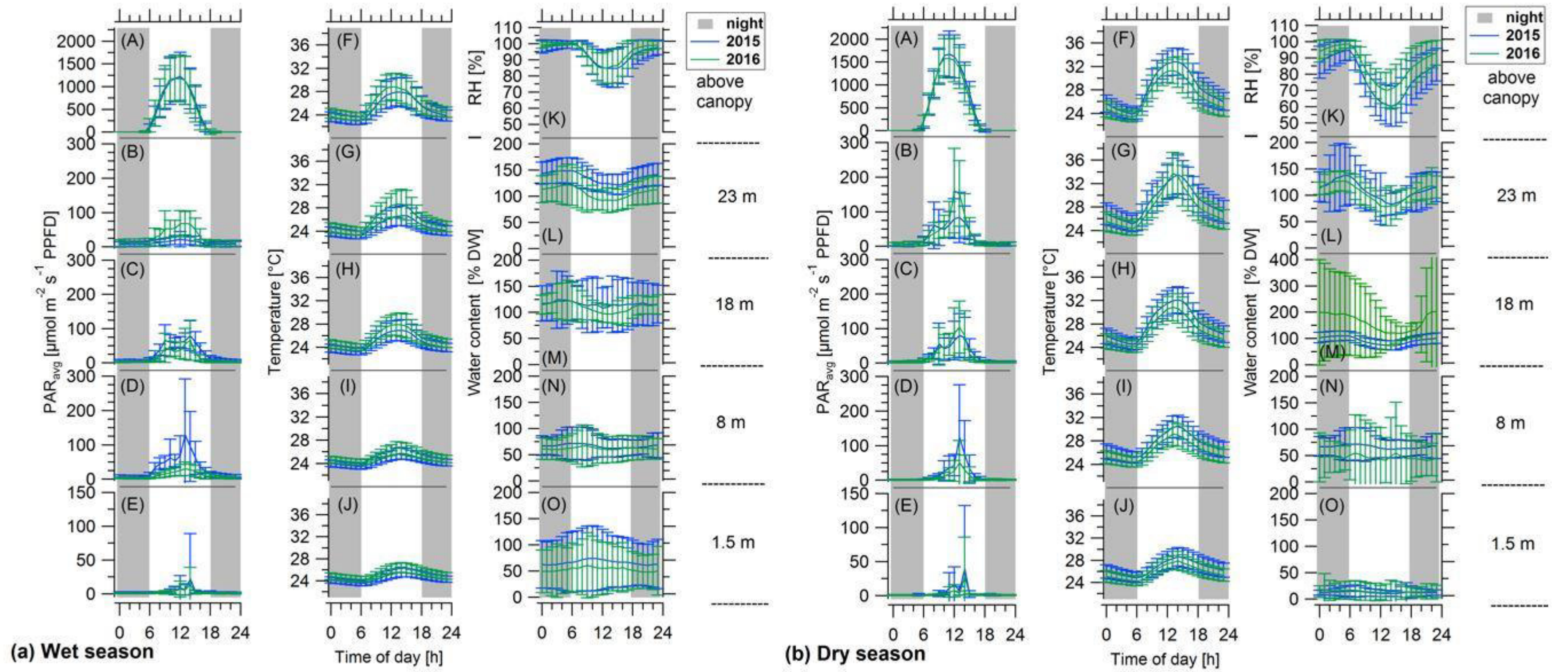


Figure 3: Mean diurnal cycles of water content (WC), temperature, and light conditions of bryophytes, and above-canopy ecophysiological, micro-meteorological, and ambient meteorological parameters during (a) wet season and (b) dry season of the years 2015 (blue lines) and 2016 (green lines) based on 30-minute intervals. The above-canopyambient meteorological parameters comprise (A) the above-canopyambient photosynthetically active radiation (PAR_{avg} at 75 m), (F) the above-canopyambient temperature (at 26 m), and (K) the relative air humidity (RH at 26 m height). Ecophysiological and The micrometeorological parameters measured on top/within epiphytic cryptogamic communities comprise (B – E) the photosynthetically active radiation (PAR) on top, (G – J) the temperature within, and (L – O) the water contentWC of cryptogamic communities at different height levels. Diel cycles were calculated from whole seasons and show hourly mean values ± SD. Data of the sensors installed at the same height level were pooled, while the above-canopyambient parameters were measured with one sensor each. Nighttime is shaded in grey (06:00 – 18:00 LT). Statistical cComparisons of maximum and minimum values and diel amplitudes of light, temperature, and humidity between seasons are shown in Table S65 – S87. Comparisons among height levels are presented in Table S9 – Table S11.

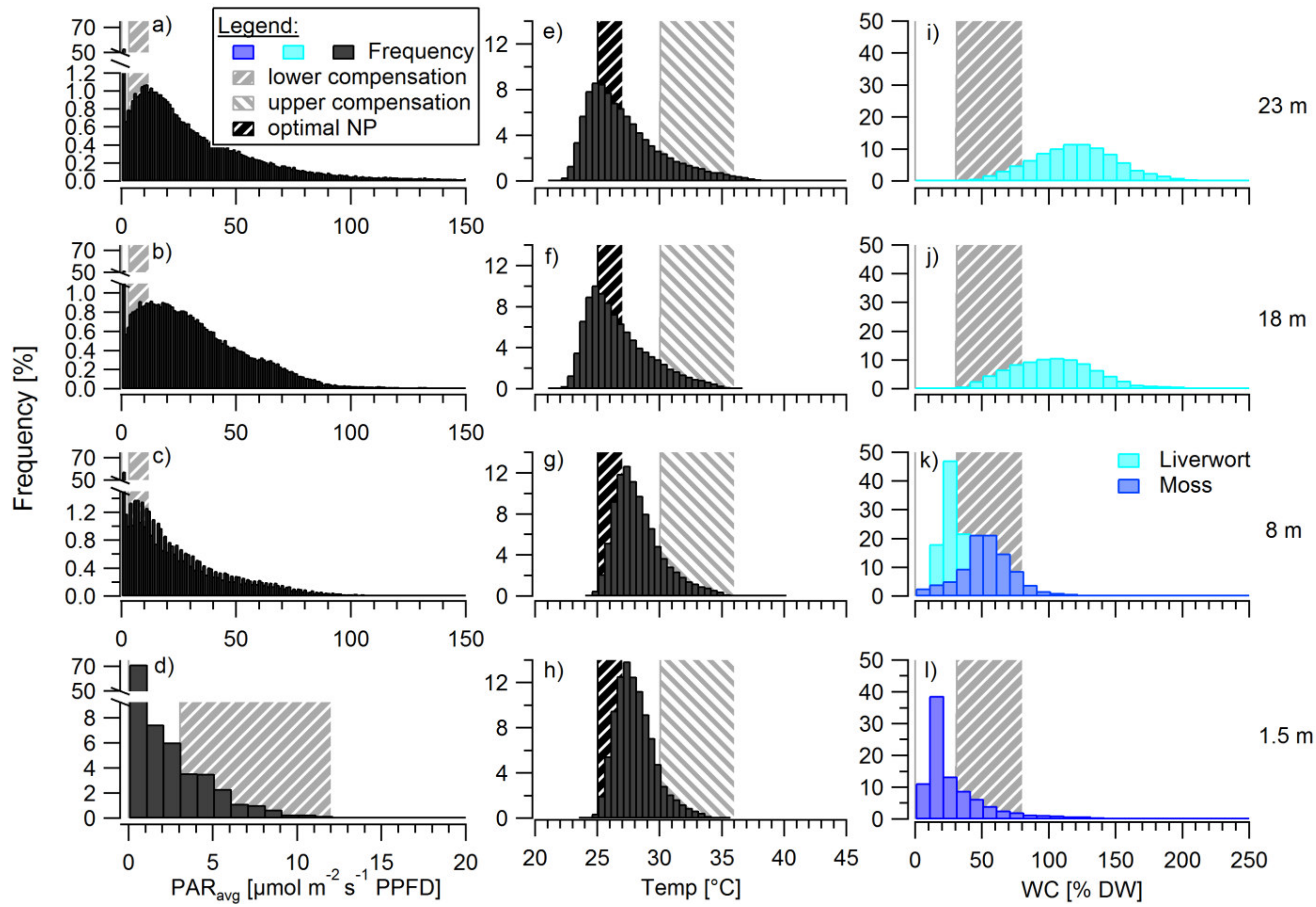


Figure 4: Frequency of photosynthetically active radiation (PAR_{avg}; a – d), temperature (Temp; e – h), and water content (WC; i – l) measured on top/within bryophytes at 1.5, 8, 18, and 23 m height within the canopy based on 30-minute intervals. Shaded~~Grey~~ areas represent the ranges of lower compensation (PAR, ~~water content~~WC)~~, and~~ upper compensation (temperature)~~ compensation~~, and temperature for optimum net photosynthesis (black shading)~~ is shown with horizontal and saturation with inclined hachure~~. Value ranges are adopted from~~ Zotz et al., (1997), Leon-Vargas et al., (2006), Romero et al., (2006),~~ Lösch (1994) and Wagner et al., (2013) (Table ~~S2~~S3). Bin sizes: PAR: 1 µmol m^{-2} s^{-1}~~ PPFD~~; temperature: 0.5 °C; WC: 10 %.

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

Contents:

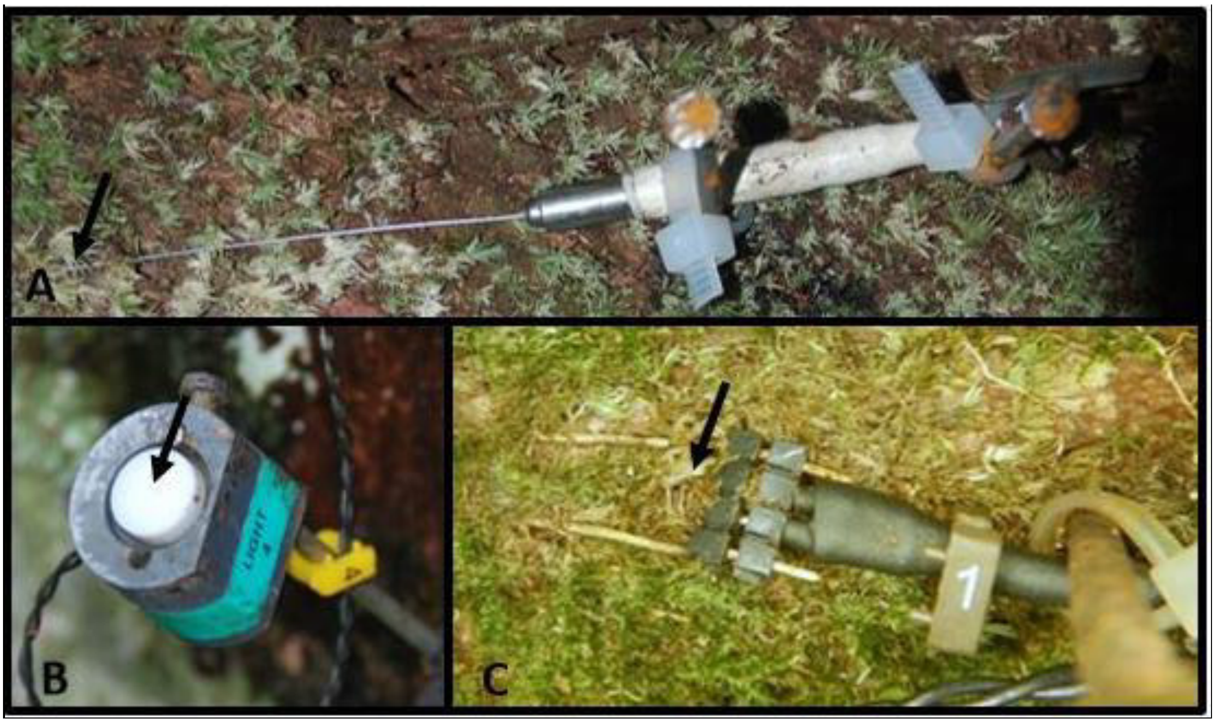


Figure S1: Examples of the temperature sensor (A), light sensor (B), and water content sensor (C) installed in epiphytic bryophytes at the ATTO site. The little arrows show the area of detection, i.e. the sensor tip of the temperature sensor, the area just below the white PTFE cap of the light sensor,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

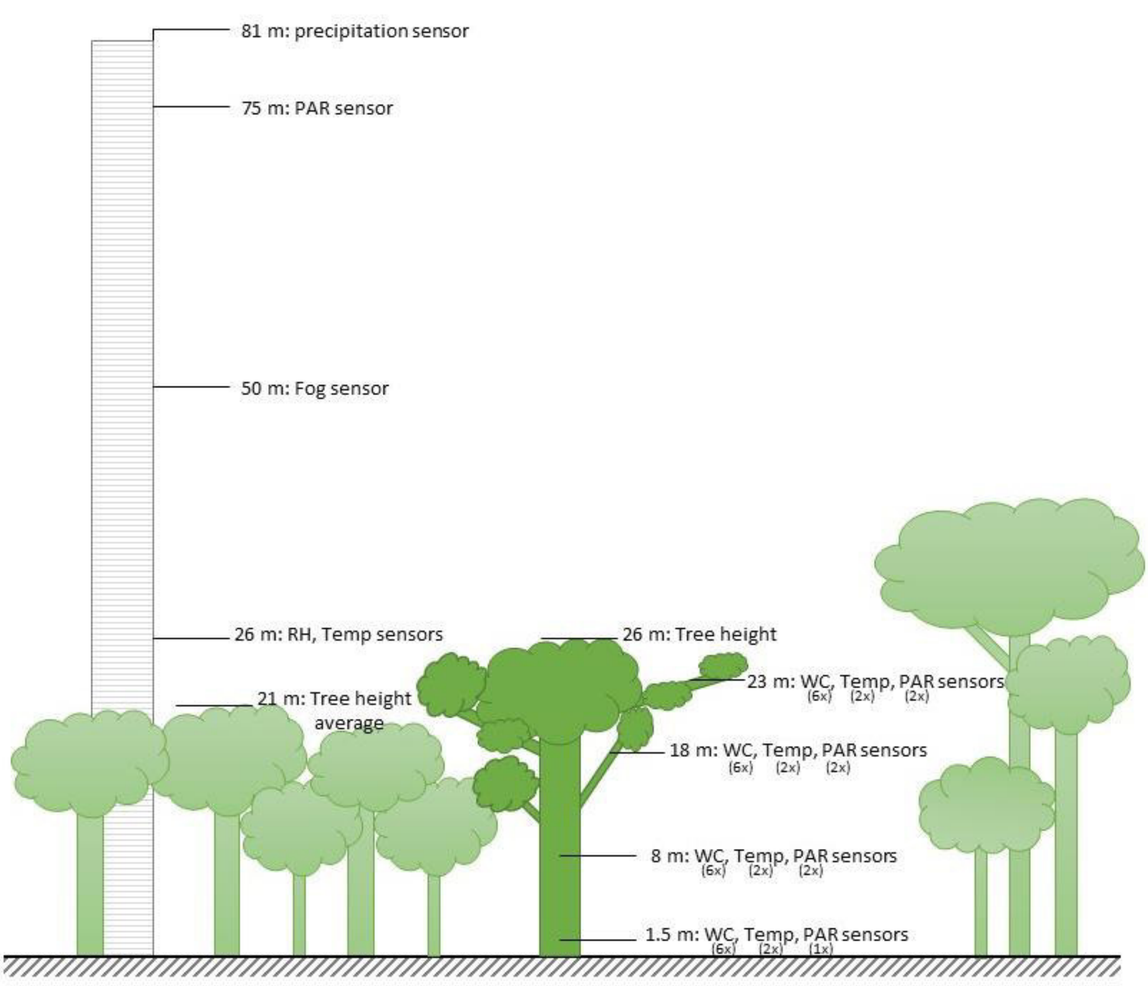


Figure S2: Schematic overview of the sensors installed at different height levels below, within, and above the canopy. The parameters water content (WC) and temperature (Temp) were measured within the bryophyte samples, the light sensors (PAR) were installed directly on top of the thalli. The average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

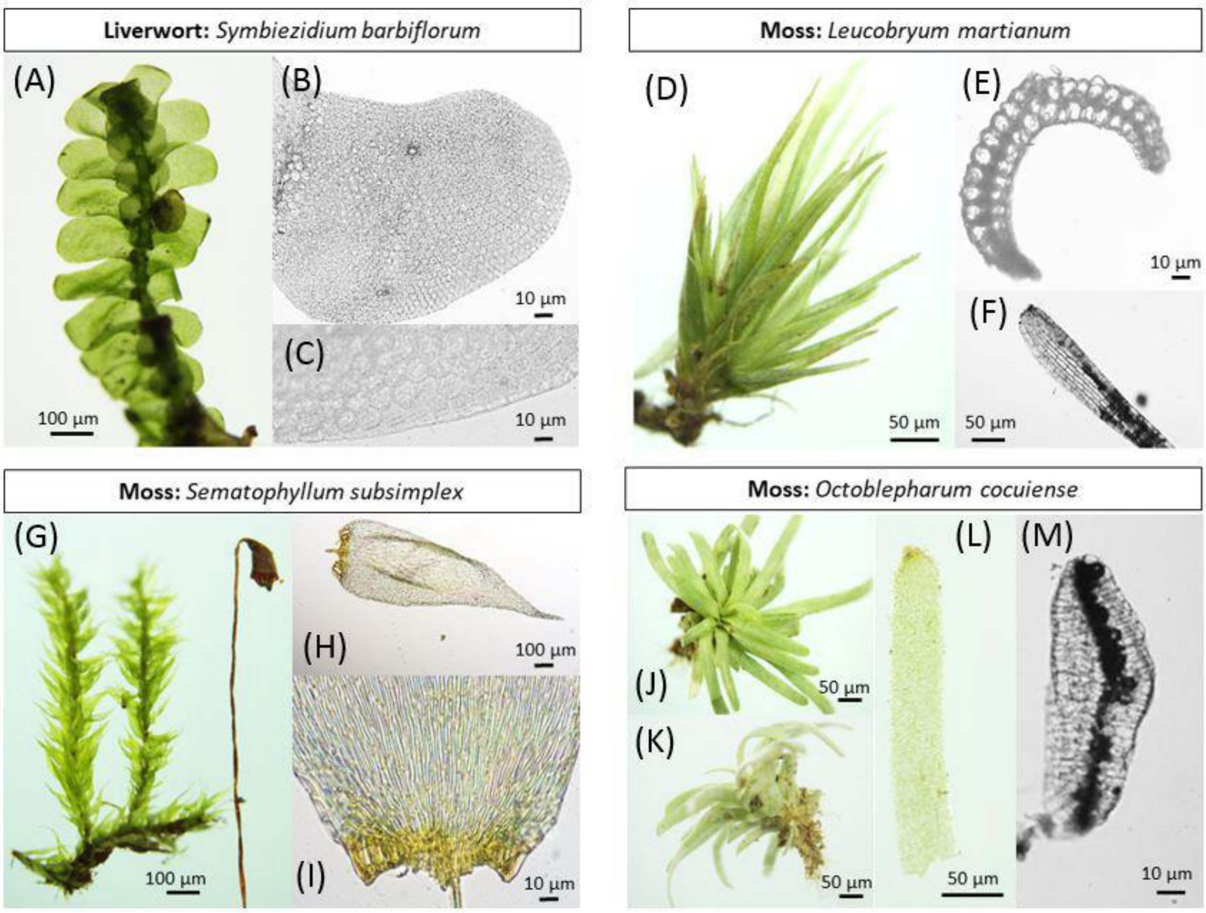
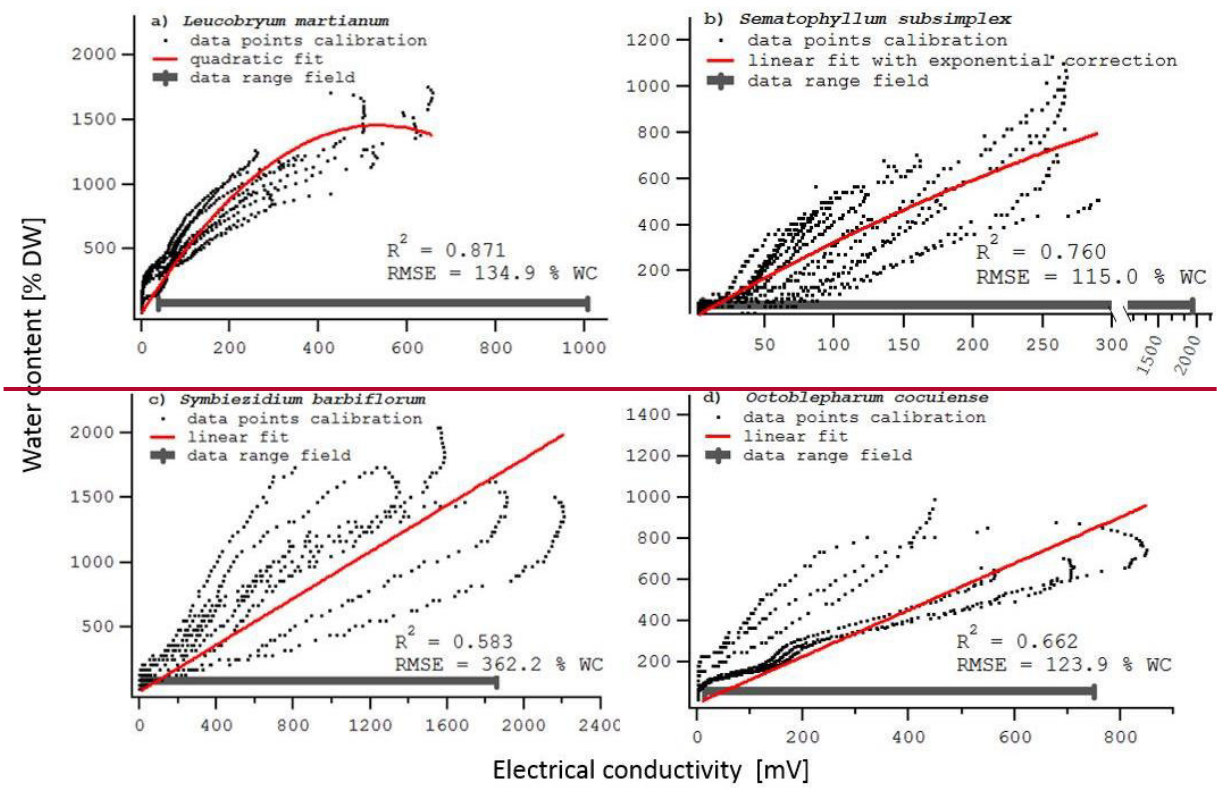


Figure S3: The four bryophyte species being used for installation of the sensors of the microclimate station. (A, D, G, J, K) overview, (B, H, L) leaf, (C, F I) cell form, and (E, M) cross section of a leaf.



~~**Figure S3:** Calibration curves of water content sensors installed within different bryophyte species. The water content [% DW] is plotted against the electrical conductivity [mV] for the species a) *Leucobryum martianum*, b) *Sematophyllum subsimplex*, c) *Symbiezidium barbiflorum*, and d) *Octoblepharum cocuiense*. Of each bryophyte species three replicates (four for *Sematophyllum subsimplex*, two for *Symbiezidium barbiflorum*) were measured over the course of three subsequent wetting and drying cycles. The dots show the measured data points and the lines represent the statistical fit. Depending opn the data, a linear fit, quadratic fit or linear fit with exponential correction was used (see methods section for further details. The vertical grey bars indicate the data range covered during the field measurements. For each fit the R^2 and RMSE are given in the graphics.~~

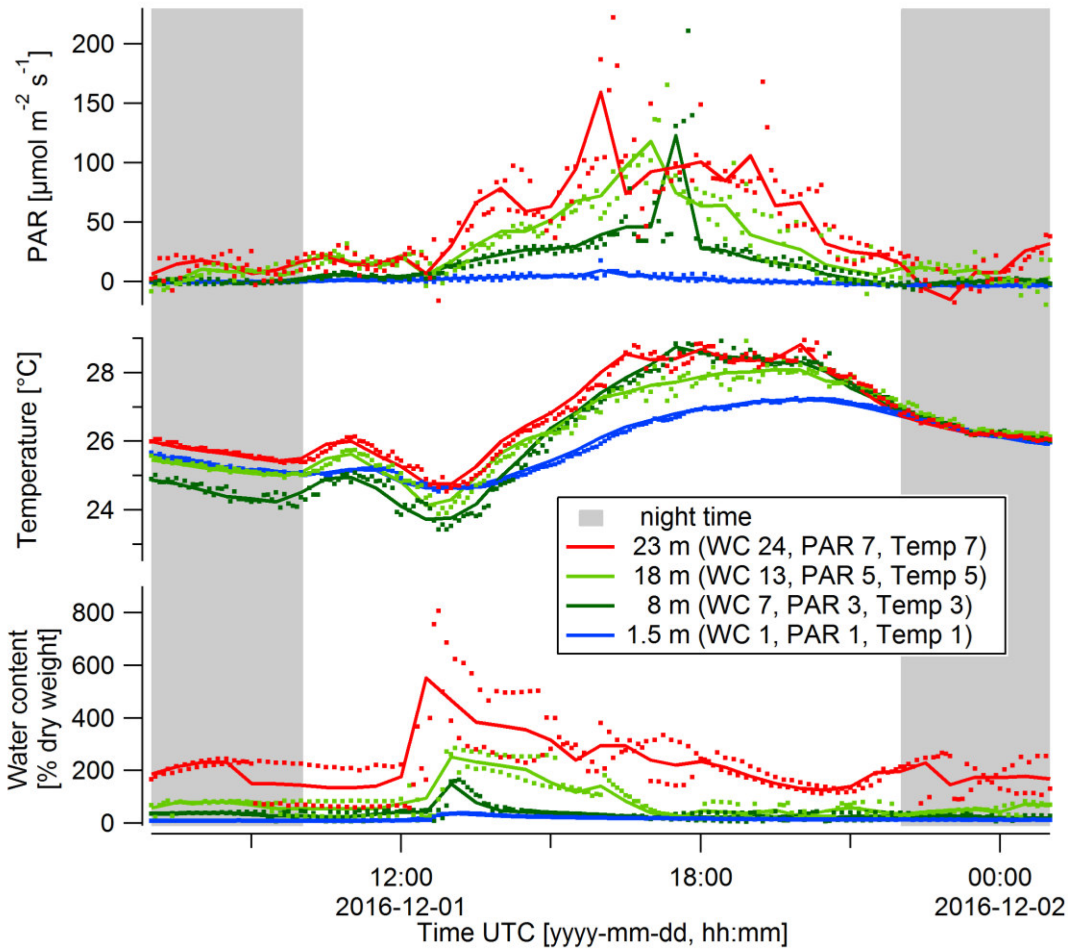


Figure S~~2~~4: Comparison of 5-minute (dots) and 30-minute (lines) ~~integrals~~ averages of exemplary sensors at each height level over a period of approx. one day in December 2016.

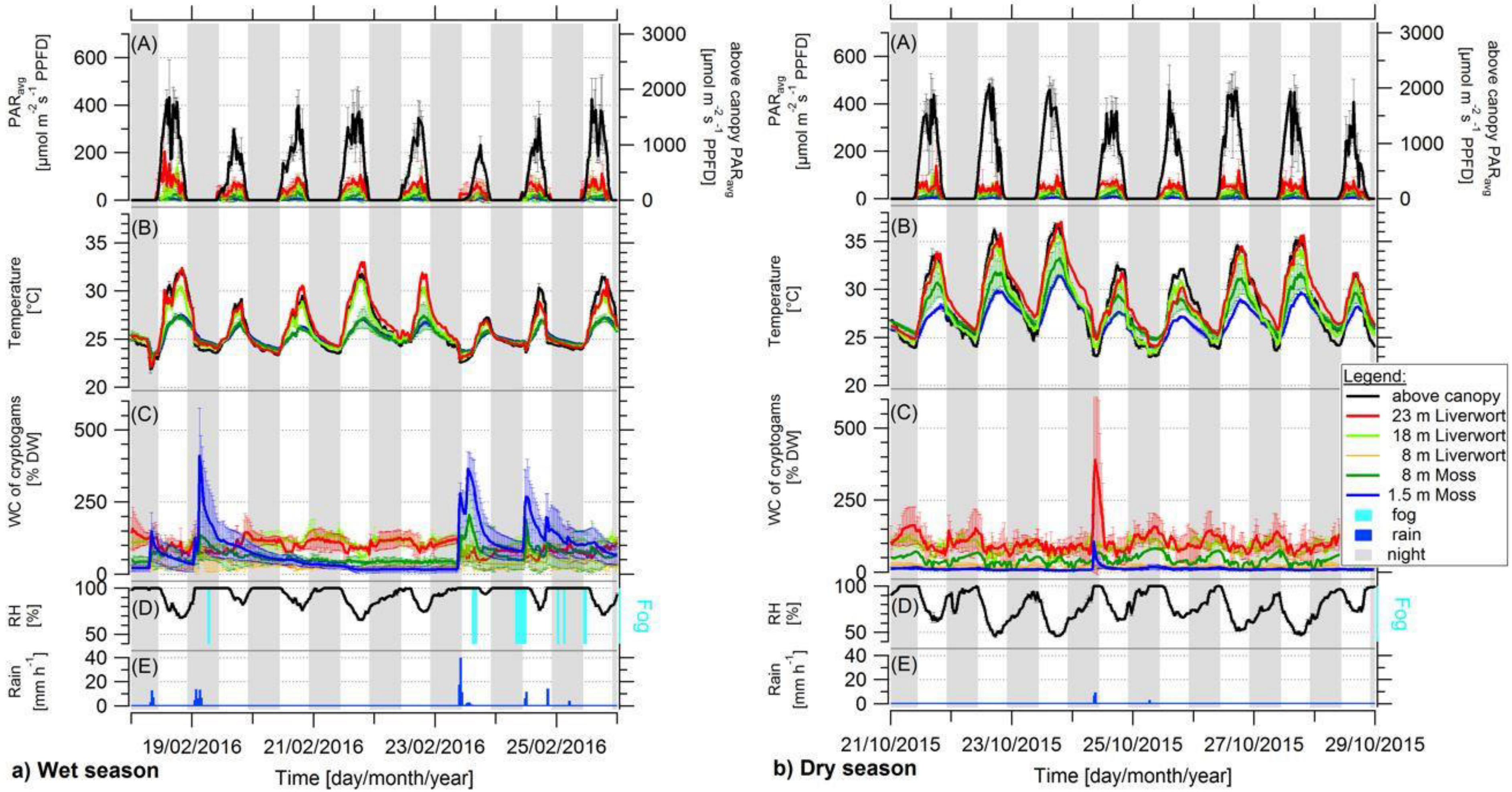


Figure S45: Representative periods during wet and dry season under the influence of El Niño,; data showing the water content (WC), temperature, and light conditions (PAR$_{avg}$) experience by bryophytes, and above-canopy meteorological conditions in the Amazonian rain forest. Shown are 8-day periods during a) the wet season 20165 and b) the dry season 20156. The micrometeorological parameters on top/within epiphytic cryptogamic communities represent (A) the photosynthetically active radiation (PAR_{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_{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. 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 night time is shaded in grey (06:00 – 18:00 LT).

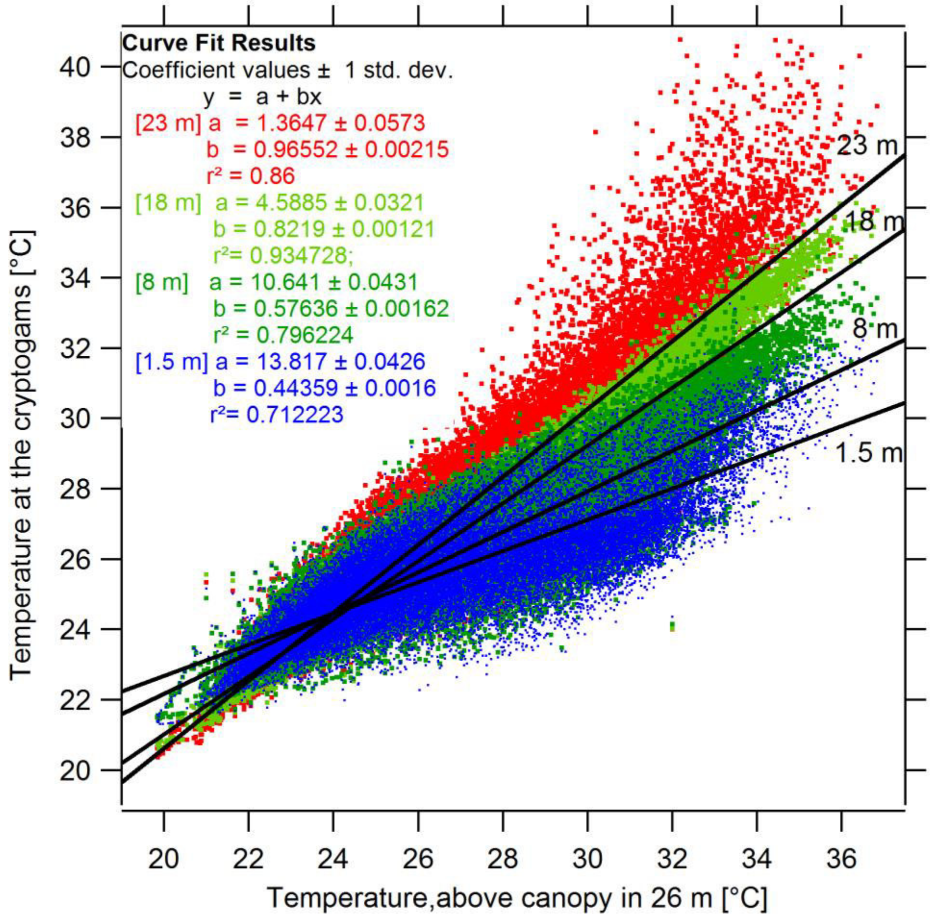


Figure S56: Microclimatic tTemperature within bryophytes compared to the above-canopy mesoclimatic ambient temperature. The temperature within bryophytes was measured at 1.5 m (blue diamonds), 8 m (dark green triangles), 18 m (light green squares), and 23 m (red crosses), while the above-canopyambient temperature was measured at 26 m height on the tower. Data present 30-minute averages with linear fits. For each height level the coefficients and the R^2 are given.

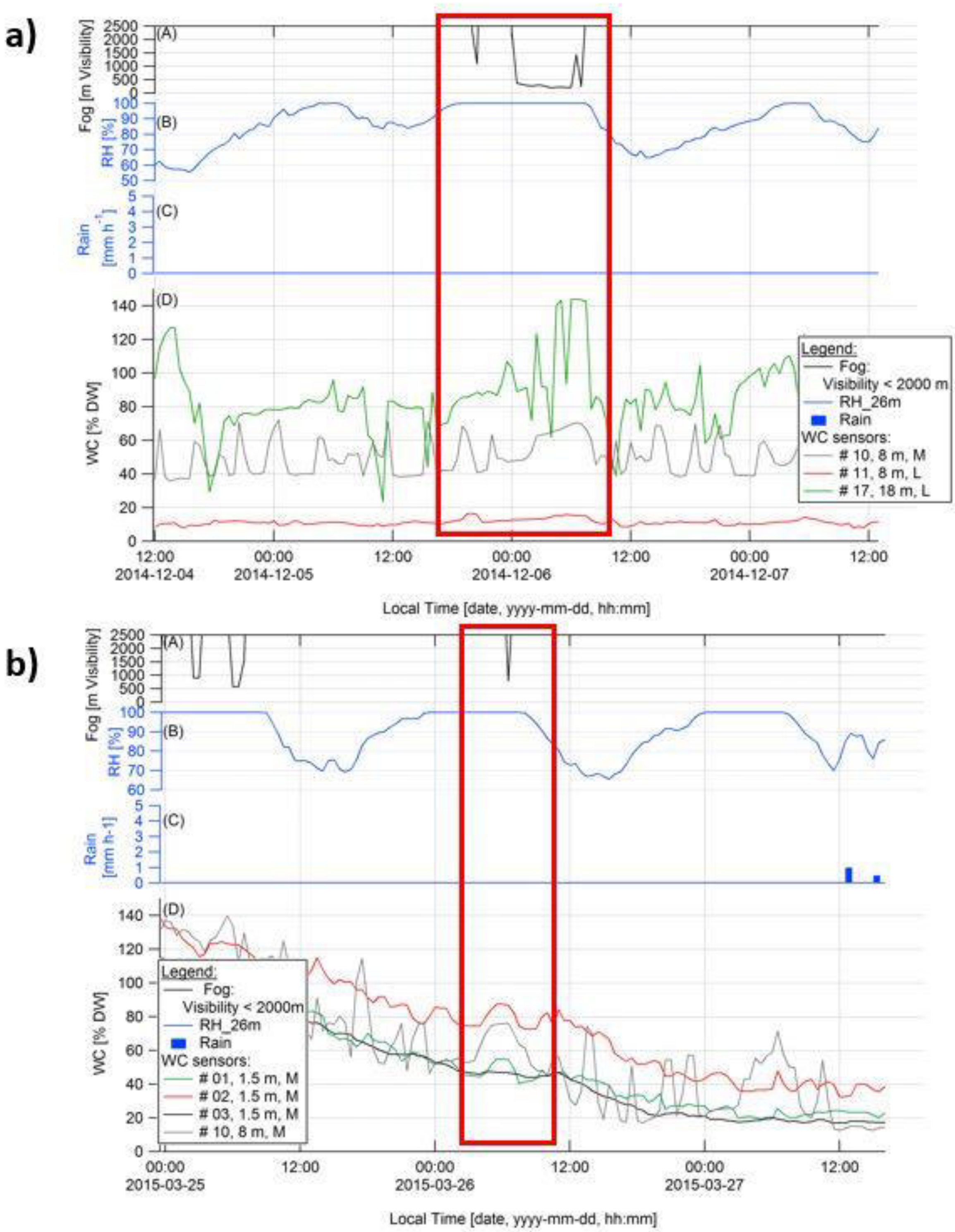


Figure S7: Two exemplary fog events and the reaction of the moisture sensors of the bryophytes (a and b). Each panel presents (A) a fog event with the parameters fog with visibility < 2000 m being defined as fog occurrence, (B) relative air humidity (RH), (C) rain, and (D) the water content (WC) of the 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.

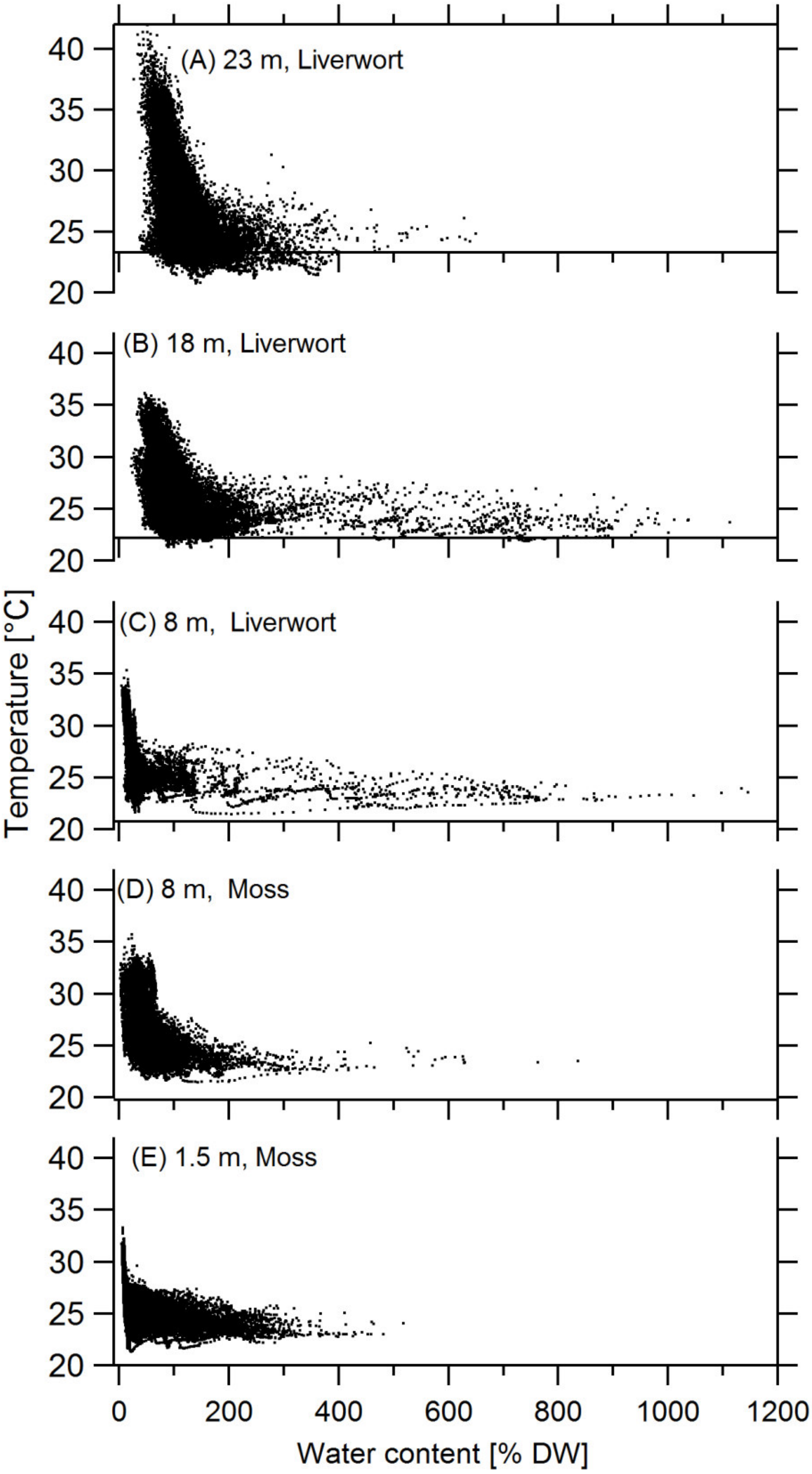


Figure S8: Temperature conditions of bryophytes related to their water content. The temperature was measured in bryophytes at different height levels along the tree. Data presented as 30-minute averages.

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Table S1a: Bryophyte species and calibration data of the water content sensors. Listed are the bryophyte species with their division (moss or liverwort)bryophyte type, their height and height zone of installation, the minimum (Min_{Field}) and the maximum (Max_{Field}) electrical conductivity assessed in the field, the maximum electrical conductivity measured during calibration (Max_{Calib}), the fit being used for the calibration (l = linear, lec = linear with exponential correction, sqrt = quadratic), the root mean square error (RMSE), and the determination coefficient R^2., and the root mean square error (RMSE). The value of RMSE is given in % dry weight (% DW). Calculations are based on 30 minute integrals of data. *) The species name cannot be verified without any doubts, however, the information of the calibration done with this species was considered for further data analysis, due to morphological properties.

Bryophyte species	Bryophyte type	Height [m]	Height zone	Min_{Field} mV	Max_{Field} mV	Max_{Calib} mV	Fit	R^2	RMSE % DW
Symbiezidium barbiflorum	Liverwort	8, 18, 23	2, 3, 4	16	1857	2207	l	0.583	362
Octoblepharum cocuiense	Moss	8	2	13	750	992	l	0.662	124
Sematophyllum subsimplex	Moss	1.5	1	5	1940	290	lec	0.760	115
Leucobryum martianum	Moss	1.5	1	40	1005	656	sqrt	0.871	135

Bryophyte species	Division	Height [m]	Height zone	RSME [% DW]	R^2
Sematophyllum subsimplex	Moss			44	0.95
Sematophyllum subsimplex	Moss			125	0.84
Sematophyllum subsimplex	Moss			35	0.95
Sematophyllum subsimplex	Moss			66	0.81
Octoblepharum cocuiense	Moss			66	0.89
Octoblepharum cocuiense	Moss				0.8
Leucobryum martianum	Moss			162	0.89
Leucobryum martianum	Moss			135	0.72
Leucobryum martianum	Moss			159	0.76
*Symbiezidium barbiflorum**	Liverwort			146	0.89
*Symbiezidium barbiflorum**	Liverwort			306	0.78
*Symbiezidium barbiflorum**	Liverwort	-	-	235	0.8
Sematophyllum subsimplex	**Moss**	**1.5**	**1**	**68**	**0.89**
Octoblepharum cocuiense	**Moss**	**8**	**2**	**85**	**0.84**
Leucobryum martianum	**Moss**	**1.5**	**1**	**152**	**0.79**
Symbiezidium barbiflorum*	**Liverwort**	**8, 18, 23**	**2, 3, 4**	**229**	**0.82**

Table S1bS1: Height of installation, and minimum and maximum values of the individual sensors of the microclimate station measuring water content, temperature, and light (PAR). For the water content sensors, also the bryophyte species are given. Based on 30-minute integralaverages.

Water content	**Height** [m]	**WC [% DW]** min	**WC [% DW]** max	**Bryophyte species**
Sensor 01	1.5	187	6601512	*Sematophyllum subsimplex*
Sensor 02	1.5	185	5431512	*Sematophyllum subsimplex*
Sensor 03	1.5	0121	6401512	*Sematophyllum subsimplex*
Sensor 04	1.5	3194	6391455	*Leucobryum martianum*
Sensor 05	1.5	5124	6451512	*Sematophyllum subsimplex*
Sensor 06	1.5	331	7301487	*Sematophyllum subsimplex*
Sensor 07	8	114	14801286	*Symbiezidium barbiflorum*
Sensor 08	8	218	1066798	*Octoblepharum cocuiense*
Sensor 09	8	316	1223950	*Octoblepharum cocuiense*
Sensor 10	8	218	1075789	*Octoblepharum cocuiense*
Sensor 11	8	330	12621130	*Symbiezidium barbiflorum*
Sensor 12	8	629	1355811	*Symbiezidium barbiflorum*
Sensor 13	18	639	1584782	*Symbiezidium barbiflorum*
Sensor 14	18	1738	1345295	*Symbiezidium barbiflorum*
Sensor 15	18	1745	1552315	*Symbiezidium barbiflorum*
Sensor 16	18	1344	1573327	*Symbiezidium barbiflorum*
Sensor 17	18	1032	1342575	*Symbiezidium barbiflorum*
Sensor 18	18	037	16421703	*Symbiezidium barbiflorum*
Sensor 19	23	1443	1283536	*Symbiezidium barbiflorum*
Sensor 20	23	45	393	*Symbiezidium barbiflorum*
Sensor 21	23	1737	1252864	*Symbiezidium barbiflorum*
Sensor 22	23	1348	1066774	*Symbiezidium barbiflorum*
Sensor 23	23	2966	893514	*Symbiezidium barbiflorum*
Sensor 24	23	068	1725492	*Symbiezidium barbiflorum*

Temperature	**Height** [m]	**Temperature [°C]** min	**Temperature [°C]** max
Sensor 01	1.5	21.1	36.3
Sensor 02	1.5	21.4	39.4
Sensor 03	8	21.6	34.7
Sensor 04	8	20.9	46.3
Sensor 05	18	20.3	38.0
Sensor 06	18	20.3	37.5
Sensor 07	23	20.8	41.2
Sensor 08	23	20.3	48.7

Light	**Height** [m]	**PAR [µmol m^{-2} s^{-1}]** min	**PAR [µmol m^{-2} s^{-1}]** max
Sensor 01	1.5	0	6341546
Sensor 02	8	0	5691461
Sensor 03	8	0	11211502
Sensor 04	18	0	5251386
Sensor 05	18	0	6151080
Sensor 06	23	0	6541326
Sensor 07	23	0	7671351

Table S1b: Bryophyte species and calibration data of the water content sensors. Listed are the bryophyte species with their division (moss or liverwort), their height and height zone of installation, the root mean square error (RMSE), and the determination coefficient R^2. *) The species name cannot be verified without any doubts, however, the information of the calibration done with this species was considered for further data analysis, due to morphological properties.

Bryophyte species	Division	Height [m]	Height zone	RSME [% DW]	R^2
Sematophyllum subsimplex	Moss			44	0.95
Sematophyllum subsimplex	Moss			125	0.84
Sematophyllum subsimplex	Moss			35	0.95
Sematophyllum subsimplex	Moss			66	0.81
Octoblepharum cocuiense	Moss			66	0.89
Octoblepharum cocuiense	Moss			103	0.8
Leucobryum martianum	Moss			162	0.89
Leucobryum martianum	Moss			135	0.72
Leucobryum martianum	Moss			159	0.76
*Symbiezidium barbiflorum**	Liverwort			146	0.89
*Symbiezidium barbiflorum**	Liverwort			306	0.78
*Symbiezidium barbiflorum**	Liverwort	-	-	235	0.8
Sematophyllum subsimplex	**Moss**	**1.5**	**1**	**68**	**0.89**
Octoblepharum cocuiense	**Moss**	**8**	**2**	**85**	**0.84**
Leucobryum martianum	**Moss**	**1.5**	**1**	**152**	**0.79**
Symbiezidium barbiflorum*	**Liverwort**	**8, 18, 23**	**2, 3, 4**	**229**	**0.82**

Table S2: Monthly mean values and standard deviations (± SD) of photosynthetically active radiation (PAR_{avg} daytime, measured ~~in~~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 ~~in~~at 81 m), and also the percentage of days when rain detection malfunctioned are listed. Fog events are given as the percentage of days. 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} ~~PPFD~~]		PAR_{max} [µmol m^{-2} s^{-1} ~~PPFD~~]		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 ~~S2~~S3: Parameters determining time range of photosynthesis and respiration. The ~~water content (WC),~~ lower water compensation point (WCP_l), ~~water saturation point (WSP), maximal water content (WC_{max}),~~ the lower light compensation point (LCP_l), the ~~light saturation point (LSP),~~ temperature for optimal net photosynthesis (T_{opt} ~~NP~~), and the upper temperature compensation point (TCP)~~$_u$), and time range of physiological activity~~ as relevant parameters have been extracted from published studies conducted at various study sites in the tropical rain forest.

Parameter	Low	High	Unit	Reference	Study site
~~WC~~	~~400~~	~~2000~~	~~% DW~~	~~Zotz et al. 1997~~	~~Panama, lower montane rain forest, 1100 m~~
WCP_l	30	80	% DW	Wagner et al 2013	Panama, low-land rain forest, 0 m
~~WCP_l~~	~~136~~	~~225~~	~~% DW~~	~~Romero et al. 2006~~	~~Costa Rica, montane oak-bamboo forest, 2900 m~~
~~WSP~~	~~349~~	~~1053~~	~~% DW~~	~~Romero et al. 2006~~	~~Costa Rica, montane oak-bamboo forest, 2900 m~~
~~WC_{max}~~	~~663~~	~~1558~~	~~% DW~~	~~Wagner et al 2013~~	~~Panama, low-land rain forest, 0 m~~
~~LCP_l~~	~~4.9~~	~~10.5~~	~~µmol m^{-2} s^{-1} PPFD~~	~~Romero et al. 2006~~	~~Costa Rica, montane oak-bamboo forest, 2900 m~~
~~LCP_l~~	~~10~~	~~35~~	~~µmol m^{-2} s^{-1} PPFD~~	~~Zotz et al. 1997~~	~~Panama, lower montane rain forest, 1100 m~~
~~LCP_l~~	~~22~~	~~69~~	~~µmol m^{-2} s^{-1} PPFD~~	~~Wagner et al 2013~~	~~Panama, low-land rain forest, 0 m~~
~~LSP~~	~~110~~	~~256~~	~~µmol m^{-2} s^{-1} PPFD~~	~~León-Vargas et al 2006~~	~~Venezuela, cloud forest, 2000-4000 m~~
~~LSP~~	~~200~~	~~400~~	~~µmol m^{-2} s^{-1} PPFD~~	~~Zotz et al. 1997~~	~~Panama, lower montane rain forest, 1100 m~~
LCP_l	3	12	µmol m^{-2} s^{-1} ~~PPFD~~	Lösch et al. 1994	Zaire, lowland rain forest, 800 m
T_{opt} ~~NP~~	24	27	°C	Wagner et al 2013	Panama, low-land rain forest, 0 m
~~T_{opt} NP~~	~~25~~		~~°C~~	~~Frahm 1990~~	~~Transvvaal, Tanzania, Venezuela, Peru, and Borneo~~
TCP~~$_u$~~	30	36~~3~~	°C	Wagner et al 2013	Panama, low-land rain forest, 0 m
~~Activity~~	~~8.5~~	~~52.2~~	~~Percentage of time~~	~~León-Vargas et al 2006~~	~~Venezuela, cloud forest, 2000-4000 m~~

Table S4: 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. Values were calculated from 30-minute intervals. N.a.: data not available.

Month	PAR_{avg} daytime[µmol m^{-2} s^{-1} ~~PPFD~~]								PAR_{max} [µmol m^{-2} s^{-1} ~~PPFD~~]							
	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 S4

	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	100~~80~~	86~~69~~	84~~54~~	67~~43~~	29~~30~~	8~~9~~	121~~127~~	67~~70~~	163~~171~~	73~~76~~
Nov 14	25.3	1.2	25.7	1.4	25.9	1.8	26.2	2.3	25~~20~~	18~~15~~	50~~32~~	11~~7~~	27~~28~~	3~~4~~	101~~106~~	58~~61~~	150~~158~~	69~~72~~
Dec 14	25.4	1.1	25.8	1.3	26.1	1.6	26.6	2.1	32~~26~~	34~~28~~	52~~33~~	14~~9~~	27~~28~~	4~~4~~	104~~110~~	55~~57~~	123~~130~~	33~~34~~
Jan 15	24.2	1.1	24.3	1.3	24.5	1.7	24.6	1.8	76~~62~~	72~~58~~	66~~42~~	20~~13~~	29~~31~~	5~~5~~	112~~118~~	59~~62~~	136~~143~~	42~~44~~
Feb 15	24.5	1.0	24.5	1.1	25.0	2.0	25.0	1.8	61~~49~~	50~~41~~	61~~39~~	20~~13~~	29~~30~~	4~~4~~	97~~102~~	30~~32~~	144~~152~~	32~~34~~
Mar 15	24.4	0.9	24.3	0.9	24.6	1.6	24.5	1.3	77~~62~~	52~~42~~	79~~51~~	38~~24~~	33~~35~~	5~~5~~	106~~111~~	40~~42~~	150~~157~~	27~~28~~
Apr 15	24.6	0.9	24.7	1.1	25.0	1.8	24.9	1.8	52~~42~~	51~~41~~	57~~37~~	15~~10~~	30~~31~~	5~~5~~	128~~135~~	58~~61~~	134~~141~~	27~~28~~
May 15	24.6	0.9	24.5	0.9	24.8	1.7	24.8	1.7	77~~63~~	63~~52~~	69~~44~~	29~~19~~	29~~30~~	4~~4~~	122~~128~~	37~~39~~	133~~140~~	27~~28~~
Jun 15	24.5	0.9	24.5	1.0	25.0	1.9	25.0	1.9	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	126~~133~~	18~~19~~	138~~145~~	28~~30~~
Jul 15	24.5	1.1	25.0	1.5	25.5	2.4	25.5	2.5	25~~20~~	16~~13~~	60~~38~~	18~~12~~	25~~26~~	5~~6~~	127~~134~~	22~~23~~	145~~153~~	73~~77~~
Aug 15	25.4	1.2	26.3	2.0	26.9	2.7	27.0	2.8	15~~12~~	7~~6~~	51~~33~~	12~~8~~	21~~22~~	5~~5~~	102~~107~~	25~~26~~	125~~132~~	46~~49~~
Sep 15	27.0	1.7	27.8	2.2	28.5	3.2	29.0	3.4	11~~9~~	12~~10~~	45~~29~~	11~~7~~	19~~20~~	5~~6~~	87~~92~~	23~~24~~	103~~109~~	46~~48~~
Oct 15	27.2	1.8	28.0	2.2	28.4	3.1	29.4	3.2	11~~9~~	10~~8~~	42~~27~~	16~~10~~	20~~21~~	5~~6~~	88~~92~~	24~~26~~	106~~111~~	64~~67~~
Nov 15	27.2	1.9	27.6	2.3	28.1	3.1	29.2	3.6	14~~12~~	11~~9~~	42~~27~~	16~~10~~	21~~22~~	10~~10~~	89~~94~~	22~~23~~	108~~113~~	53~~56~~
Dec 15	27.3	1.6	27.9	2.0	28.2	2.6	29.4	3.4	13~~11~~	8~~7~~	40~~25~~	16~~10~~	20~~21~~	8~~9~~	89~~93~~	22~~23~~	104~~110~~	46~~49~~
Jan 16	27.4	1.8	28.0	2.2	28.4	3.0	29.4	3.8	14~~12~~	11~~9~~	42~~27~~	18~~12~~	19~~20~~	8~~9~~	86~~90~~	24~~25~~	108~~113~~	41~~43~~
Feb 16	25.2	1.0	25.4	1.2	25.8	2.1	26.2	2.5	66~~53~~	72~~58~~	60~~38~~	38~~24~~	31~~33~~	19~~20~~	105~~111~~	26~~27~~	124~~130~~	43~~45~~
Mar 16	25.2	0.9	25.1	0.9	25.4	1.6	25.6	1.8	61~~49~~	52~~42~~	56~~36~~	25~~16~~	33~~34~~	15~~15~~	119~~125~~	30~~31~~	106~~111~~	30~~31~~
Apr 16	25.2	1.0	25.2	1.1	25.5	1.7	25.7	2.0	52~~42~~	34~~28~~	75~~48~~	41~~26~~	41~~43~~	22~~23~~	n.a. ~~n.a.~~	n.a. ~~n.a.~~	108~~113~~	37~~39~~
May 16	25.3	1.0	25.3	1.2	25.8	1.9	26.1	2.3	35~~28~~	26~~21~~	59~~38~~	27~~18~~	21~~22~~	11~~12~~	n.a. ~~n.a.~~	n.a. ~~n.a.~~	100~~105~~	40~~42~~
Jun 16	24.6	1.1	24.6	1.3	25.3	2.2	25.8	2.8	25~~21~~	13~~10~~	58~~37~~	27~~17~~	n.a.~~n.a.~~	n.a.~~n.a.~~	n.a.~~n.a.~~	n.a.~~n.a.~~	111~~117~~	25~~26~~
Jul 16	24.8	1.2	25.3	1.7	25.9	2.5	26.7	3.4	21~~17~~	16~~13~~	45~~29~~	19~~12~~	n.a.~~n.a.~~	n.a.~~n.a.~~	n.a.~~n.a.~~	n.a.~~n.a.~~	117~~123~~	38~~40~~
Aug 16	25.7	1.8	26.3	2.4	26.9	3.0	28.0	4.1	14~~11~~	17~~14~~	46~~29~~	65~~41~~	n.a. ~~n.a.~~	n.a. ~~n.a.~~	n.a. ~~n.a.~~	n.a. ~~n.a.~~	100~~105~~	25~~26~~
Sep 16	25.5	1.3	25.9	1.7	26.4	2.6	27.1	3.3	16~~13~~	21~~17~~	43~~28~~	24~~15~~	n.a. ~~n.a.~~	n.a. ~~n.a.~~	n.a. ~~n.a.~~	n.a. ~~n.a.~~	n.a.~~-~~	n.a.~~-~~
Oct 16	26.2	1.6	26.8	1.9	27.3	2.9	28.0	3.4	11~~9~~	4~~4~~	n.a.~~-~~	n.a.~~-~~	n.a. ~~n.a.~~	n.a.~~n.a.~~	~~n.a.~~	~~n.a.~~	n.a.~~-~~	n.a.~~-~~
Nov 16	25.9	1.7	26.5	2.1	27.1	2.8	28.0	3.4	19~~15~~	18~~15~~	60~~38~~	77~~49~~	87~~92~~	160~~168~~	162~~170~~	146~~153~~	117~~123~~	40~~42~~
Dec 16	25.4	1.3	25.0	1.7	25.3	2.1	25.6	2.5	39~~31~~	40~~32~~	83~~53~~	50~~32~~	207~~217~~	217~~228~~	295~~310~~	214~~225~~	176~~185~~	80~~84~~

Table S5 Seasonal mean values and, standard deviations (± SD), and statistically significant differences between of the different height levels and above canopyambient conditions for the parameters photosynthetically active radiation (PAR_{avg}), daily maximum of photosynthetically active radiation (PAR_{max}), temperature, and above canopyambient relative humidity/water content (WC) of bryophytes. Values measured as above canopyambient conditions and within/on top of bryophytes at four height levels. Mean values for the respective seasons were calculated from 5-minute intervals of the years 2015 and 2016. Due to the absence of normal distribution and variance homogeneity a non-parametric Kruskal-Wallis test with post hoc test was performed to compare values obtained for different seasons.

Height	**PAR_{avg} daytime [µmol m^{-2} s^{-1} PPFD]**		**PAR_{max} [µmol m^{-2} s^{-1} PPFD]**		**Temperature [°C]**		**RH (above canopy), WC [%]**	
[m]	Mean	± SD	Mean	± SD	Mean	± SD	Mean	± SD
Wet season								
above canopy	738	566	2086	515	25.6	2.5	143	36
23 Liverwort	30	3	248	194	25.3	2.0	125110	3337
18 Liverwort	39	12	282	175	25.2	1.9	11332	3711
8 Liverwort	31	26	144	194	24.9	1.1	3141	1021
8 Moss							6448	2944
1.5 Moss	4	15	114	224	24.9	1.0	60143	5036
p	-	≤ 0.001 -	-	≤ 0.001 -		≤ 0.001 -	-	
Transitional season Wet-Dry								
above canopy	861	649	2227	182	25.8	3.0	143	57
23 Liverwort	41	72	414	252	25.7	2.8	128133	4120
18 Liverwort	44	54	351	123	25.4	2.3	12726	206
8 Liverwort	66	88	165	218	24.9	1.4	2538	515
8 Moss							549	2112
1.5 Moss	2	12	61	102	24.6	1.1	24143	1557
p	-	≤ 0.001 -	-	≤ 0.001 -		≤ 0.001 -	-	
Dry season								
above canopy	973	647	2100	609	26.7	3.4	119	52
23 Liverwort	55	9	503	231	27.2	3.5	122152	52121
18 Liverwort	41	13	412	190	26.5	2.9	10756	5288
8 Liverwort	23	16	295	268	26.0	2.1	3230	2823
8 Moss							5113	3311
1.5 Moss	6	25	209	299	25.5	1.7	23119	2052
p	-	≤ 0.001 -	-	≤ 0.001 -		≤ 0.001 -	-	
Transitional season Dry-Wet								
above canopy	785	617	1988	509	26.5	3.3	141	67
23 Liverwort	55	91	530	297	27.2	3.7	130202	48159
18 Liverwort	37	28	185	109	26.6	3.0	13772	75100
8 Liverwort	21	47	269	178	26.3	2.5	6142	4923
8 Moss							5627	2434
1.5 Moss	4	20	107	113	26.0	2.1	35141	3367
p	-	≤ 0.001 -	-	≤ 0.001 -		≤ 0.001 -	-	

Table S~~6~~5: Daily maximum values of the photosynthetically active radiation (PAR_{max}), the temperature ($Temp_{max}$), and the ~~ambient relative humidity/~~water content (WC_{max}) of epiphytic bryophytes. Mean values and~~,~~ standard deviations (± SD)~~, significance, and p-values~~ are shown for dry and wet seasons of the two years 2015 and 2016. For the above-canopy~~mbient~~ data maximum air humidity (RH) values measured at 26 m are shown, while for the bryophytes the water content was assessed. Above-canopy~~mbient~~ light intensity was measured at 75 m, above-canopy~~mbient~~ temperature and relative air humidity at 26 m.~~. Due to the absence of normal distribution and variance homogeneity a non-parametric Kruskal-Wallis test with post hoc test was performed to compare values obtained for different seasons.~~ Data of the sensors installed at the same height level were pooled, while the above-canopy parameters were measured with one sensor each.

Season	PAR_{max} [µmol m^{-2} s^{-1} ~~PPFD~~] Mean	± SD	$Temp_{max}$ [°C] Mean	± SD	RH_{max} (above canopy), WC_{max} [%] Mean	± SD
above-canopy						
Dry15	1966	730	33.5	2.1	96	5
Dry16	2232	425	32.3	1.8	99	2
Wet15	2089	515	28.9	2.4	99	3
Wet16	2084	517	30.4	1.9	100	1
23 m Liverwort						
Dry15	431	239	35.8	3.9	186~~195~~	262~~275~~
Dry16	575	260	37.4	4.7	171~~179~~	67~~70~~
Wet15	167	202	28.4	2.5	175~~183~~	43~~46~~
Wet16	329	223	31.8	3.2	160~~168~~	73~~77~~
18 m Liverwort						
Dry15	381	207	33.3	2.0	126~~132~~	16~~16~~
Dry16	443	204	32.8	2.2	252~~265~~	274~~287~~
Wet15	274	208	28.4	1.9	169~~178~~	112~~118~~
Wet16	289	188	29.6	1.7	144~~152~~	89~~32~~
8 m Liverwort						
Dry15					29~~30~~	14~~14~~
Dry16					232~~244~~	377~~396~~
Wet15					36~~38~~	12~~12~~
Wet16					62~~65~~	96~~65~~
8 m Moss						
Dry15	414	381	32.0	3.2	68~~44~~	13~~9~~
Dry16	175	258	31.0	3.9	65~~42~~	8~~5~~
Wet15	246	395	26.5	1.5	98~~63~~	65~~42~~
Wet16	44	88	27.8	1.8	103~~66~~	92~~59~~
1.5 m Moss						
Dry15	290	369	29.3	1.6	25~~21~~	42~~36~~
Dry16	127	173	29.0	2.5	33~~27~~	100~~82~~
Wet15	132	284	26.0	1.0	113~~92~~	102~~83~~
Wet16	96	140	27.0	1.0	116~~94~~	100~~81~~

Table S86: Daily amplitudes of the photosynthetically active radiation (PAR_{amp}), the temperature ($Temp_{amp}$), and the ambient relative humidity/water content (WC_{amp}) of epiphytic bryophytes. Mean values and, standard deviations (± SD), significance, and p-values are shown for dry and wet seasons of the two years 2015 and 2016. For the above-canopymbient data maximum air humidity (RH) values measured at 26 m are shown, while for the bryophytes the water content was assessed. Above-canopymbient light intensity was measured at 75 m, above-canopymbient temperature and relative air humidity at 26 m. Due to the absence of normal distribution and variance homogeneity a non-parametric Kruskal-Wallis test with post hoc test was performed to compare values obtained for different seasons. Data of the sensors installed at the same height level were pooled, while the above-canopy parameters were measured with one sensor each.

Season	PAR_{amp} [µmol m^{-2} s^{-1} PPFD] Mean	± SD	$Temp_{amp}$ [°C] Mean	± SD	RH_{amp} (above canopy), WC_{amp} [%] Mean	± SD
above-canopy						
Dry15	1966	730	9.8	2.1	39	10
Dry16	2232	425	9.3	1.6	35	8
Wet15	2089	515	6.3	2.8	18	13
Wet16	2084	517	7.0	1.8	23	9
23 m Liverwort						
Dry15	431	239	11.2	3.2	132139	258271
Dry16	575	260	13.2	4.5	109118	6566
Wet15	167	202	5.3	2.4	7376	4346
Wet16	329	223	8.1	3.1	9599	7175
18 m Liverwort						
Dry15	381	207	9.3	1.6	7074	2122
Dry16	443	204	9.1	1.9	176171	269261
Wet15	274	208	5.5	1.8	112117	98103
Wet16	289	188	6.0	1.7	7276	3739
8 m Liverwort						
Dry15					1819	1314
Dry16					240216	396391
Wet15					1112	66
Wet16					4144	5659
8 m Moss						
Dry15	414	381	7.0	3.2	4529	1912
Dry16	175	258	6.8	3.9	5435	85
Wet15	246	395	3.1	1.4	5837	6441
Wet16	44	88	3.7	1.9	6844	8353
1.5 Moss						
Dry15	290	369	4.4	1.2	1613	4135
Dry16	127	173	4.9	2.4	2319	8872
Wet15	132	284	2.5	1.0	7360	8973
Wet16	96	140	2.8	1.0	8569	8872

Table S7: Daily minimum values of the photosynthetically active radiation (PAR_{min}), the temperature ($Temp_{min}$), and the~~ ambient relative humidity/~~ water content (WC_{min}) of epiphytic bryophytes. Mean values and~~,~~ standard deviations (± SD)~~, significance, and p-values~~ are shown for dry and wet seasons of the two years 2015 and 2016. For the above-canopy~~mbient~~ data maximum air humidity (RH) values measured at 26 m are shown, while for the bryophytes the water content was assessed. Above-canopy~~mbient~~ light intensity was measured at 75 m, above-canopy~~mbient~~ temperature and relative air humidity at 26 m. ~~Due to the absence of normal distribution and variance homogeneity a non-parametric Kruskal-Wallis test with post hoc test was performed to compare values obtained for different seasons.~~Data of the sensors installed at the same height level were pooled, while the above-canopy parameters were measured with one sensor each.

Season	PAR_{min} [µmol m^{-2} s^{-1} ~~PPFD~~] Mean	± SD	$Temp_{min}$ [°C] Mean	± SD	RH_{min} (above canopy), WC_{min} [%] Mean	± SD
above-canopy						
Dry15	0	0	23.7	1.1	57	11
Dry16	0	0	23.1	0.9	65	8
Wet15	0	0	22.6	1.7	81	12
Wet16	0	0	23.5	0.7	77	9
23 m Liverwort						
Dry15	0	0	24.7	1.5	54~~56~~	18~~19~~
Dry16	0	0	24.1	1.3	59~~60~~	19~~20~~
Wet15	0	0	23.1	0.7	102~~107~~	18~~19~~
Wet16	0	0	23.6	0.6	66~~69~~	23~~25~~
18 m Liverwort						
Dry15	0	0	24.0	1.0	55~~58~~	23~~24~~
Dry16	0	0	23.7	1.0	89~~93~~	82~~86~~
Wet15	0	0	22.9	0.6	57~~60~~	34~~36~~
Wet16	0	0	23.6	0.6	72~~76~~	25~~26~~
8 m Liverwort						
Dry15					11~~11~~	4~~5~~
Dry16					26~~27~~	23~~23~~
Wet15					25~~26~~	10~~11~~
Wet16					20~~21~~	13~~14~~
8 m Moss						
Dry15	0	0	25.0	1.0	24~~15~~	13~~8~~
Dry16	0	0	24.2	0.9	10~~8~~	7~~6~~
Wet15	0	0	23.4	0.5	41~~26~~	18~~12~~
Wet16	0	0	24.0	0.5	35~~22~~	21~~14~~
1.5 m Moss						
Dry15	0	0	24.8	1.0	9~~7~~	6~~5~~
Dry16	0	0	24.1	0.9	10~~8~~	28~~23~~
Wet15	0	0	23.5	0.5	40~~32~~	30~~24~~
Wet16	0	0	24.1	0.5	31~~26~~	29~~23~~

Table S9: Daily maximum of the photosynthetically active radiation (PAR_{max}), the temperature ($Temp_{max}$), and the ambient relative humidity/water content (WC_{max}) of epiphytic bryophytes. Mean values, standard deviations (± SD), significance, and p-values are shown for dry and wet seasons of the two years 2015 and 2016. For the ambient data maximum air humidity (RH) values are shown, while for the bryophytes the water content was assessed. Ambient light intensity was measured at 75 m, ambient temperature and relative air humidity at 26 m. Due to the absence of normal distribution and variance homogeneity a non-parametric Kruskal-Wallis test with post hoc test was performed to compare values obtained for different seasons.

-	PAR_{max} [µmol m^{-2} s^{-1} PPFD]				$Temp_{max}$ [°C]				WC_{max} [%]			
Height [m]	**Mean**	**± SD**	**sig.**	**p**	**Mean**	**± SD**	**sig.**	**p**	**Mean**	**± SD**	**sig.**	**P**
Dry season 2015					-			-				
above canopy	1966	730	d	0.000	33.5	2.1	c	0.000	-	-	-	-
23 Liverwort	431	239	c		35.8	3.9	d	-	195	275		
18 Liverwort	381	207	bc		33.3	2.0	c	-	132	16		
8 Liverwort									30	14		
8 Moss	414	381	b		32.0	3.2	b	-	44	9		
1.5 Moss	290	369	a	-	29.3	1.6	a	-	21	36		
Dry season 2016					-			-				
above canopy	2232	425	d	0.000	32.3	1.8	c	0.000				
23 Liverwort	575	260	c		37.4	4.7	d	-	179	70		
18 Liverwort	443	204	b		32.8	2.2	c	-	265	287		
8 Liverwort									244	396		
8 Moss	175	258	a		31.0	3.9	b	-	42	5		
1.5 Moss	127	173	a	-	29.0	2.5	a	-	27	82		
Wet season 2015					-			-				
above canopy	2089	515	d	0.000	28.9	2.4	c	0.000				
23 Liverwort	167	202	c		28.4	2.5	c	-	183	46		
18 Liverwort	274	208	b		28.5	1.9	c	-	178	118		
8 Liverwort									38	12		
8 Moss	246	395	ac		26.5	1.5	b	-	63	42		
1.5 Moss	132	284	a	-	26.0	1.0	a	-	92	83		
Wet season 2016					-			-				
above canopy	2084	517	d	0.000	30.4	1.9	cd	0.000				
23 Liverwort	329	223	c		31.8	3.2	cd	-	168	77		
18 Liverwort	289	188	c		29.6	1.7	c	-	152	32		
8 Liverwort									65	65		
8 Moss	44	88	b		27.8	1.8	b	-	66	59		
1.5 Moss	96	140	a	-	27.0	1.0	a	-	94	81		

Table S10: Daily minimum of the photosynthetically active radiation (PAR_{min}), the temperature ($Temp_{min}$), and the ambient relative humidity/water content (WC_{min}) of epiphytic bryophytes. Mean values, standard deviations (± SD), significance, and p-values are shown for dry and wet seasons of the two years 2015 and 2016. For the ambient data maximum air humidity (RH) values are shown, while for the bryophytes the water content was assessed. Ambient light intensity was measured at 75 m, ambient temperature and relative air humidity at 26 m. Due to the absence of normal distribution and variance homogeneity a non-parametric Kruskal-Wallis test with post hoc test was performed to compare values obtained for different seasons.

-	PAR_{min} [µmol m^{-2} s^{-1} PPFD]				$Temp_{min}$ [°C]				WC_{min} [%]			
Height [m]	**Mean**	**± SD**	**sig.**	**p**	**Mean**	**± SD**	**sig.**	**p**	**Mean**	**± SD**	**sig.**	**p**
Dry season 2015					-			-				
above canopy	0	0	a	1.000	23.7	1.1	c	0.000	-	-	-	-
23 Liverwort	0	0	a		24.7	1.5	b	-	56	19		
18 Liverwort	0	0	a		24.0	1.0	c	-	58	24		
8 Liverwort									11	5		
8 Moss	0	0	a		25.0	1.0	a	-	15	8		
1.5 Moss	0	0	a	-	24.8	1.0	ab	-	7	5		
Dry season 2016					-			-				
above canopy	0	0	a	1.000	23.1	0.9	c	0.000				
23 Liverwort	0	0	a		24.1	1.3	a	-	60	20		
18 Liverwort	0	0	a		23.7	1.0	b	-	93	86		
8 Liverwort									27	23		
8 Moss	0	0	a		24.2	0.9	a	-	8	6		
1.5 Moss	0	0	a	-	24.1	0.9	a	-	8	23		
Wet season 2015					-			-				
above canopy	0	0	a	1.000	22.6	1.7	b	0.000				
23 Liverwort	0	0	a		23.1	0.7	c	-	107	19		
18 Liverwort	0	0	a		22.9	0.6	b	-	60	36		
8 Liverwort									26	11		
8 Moss	0	0	a		23.4	0.5	a	-	26	12		
1.5 Moss	0	0	a	-	23.5	0.5	a	-	32	24		
Wet season 2016					-			-				
above canopy	0	0	a	1.000	23.5	0.7	b	0.000				
23 Liverwort	0	0	a		23.6	0.6	b	-	69	25		
18 Liverwort	0	0	a		23.6	0.6	b	-	76	26		
8 Liverwort									21	14		
8 Moss	0	0	a		24.0	0.5	a	-	22	14		
1.5 Moss	0	0	a	-	24.1	0.5	a	-	26	23		

Table S11: Daily amplitudes of the photosynthetically active radiation (PAR_{amp}), the temperature ($Temp_{amp}$), and the ambient relative humidity/water content (WC_{amp}) of epiphytic bryophytes. Mean values, standard deviations (± SD), significance, and p-values are shown for dry and wet seasons of the two years 2015 and 2016. For the ambient data maximum air humidity (RH) values are shown, while for the bryophytes the water content was assessed. Ambient light intensity was measured at 75 m, ambient temperature and relative air humidity at 26 m. Due to the absence of normal distribution and variance homogeneity a non-parametric Kruskal-Wallis test with post hoc test was performed to compare values obtained for different seasons.

-	PAR_{amp} [µmol m^{-2} s^{-1} PPFD]				$Temp_{amp}$ [°C]				WC_{amp} [%]			
Height [m]	**Mean**	**± SD**	**sig.**	**p**	**Mean**	**± SD**	**sig.**	**p**	**Mean**	**± SD**	**sig.**	**p**
Dry season 2015					-			-				
above canopy	1966	730	d	0.000	9.8	2.1	de	0.000	-	-	-	-
23 Liverwort	431	239	c		11.2	3.2	d	-	139	271		
18 Liverwort	381	207	bc		9.3	1.6	c	-	74	22		
8 Liverwort									19	14		
8 Moss	414	381	b		7.0	3.2	b	-	29	12		
1.5 Moss	290	369	a	-	4.4	1.2	a	-	13	35		
Dry season 2016					-			-				
above canopy	2232	425	d	0.000	9.3	1.6	b	0.000				
23 Liverwort	575	260	c		13.2	4.5	d	-	118	66		
18 Liverwort	443	204	b		9.1	1.9	c	-	171	261		
8 Liverwort									216	391		
8 Moss	175	258	a		6.8	3.9	b	-	35	5		
1.5 Moss	127	173	a	-	4.9	2.4	a	-	19	72		
Wet season 2015					-			-				
above canopy	2089	515	d	0.000	6.3	2.8	c	0.000				
23 Liverwort	167	202	c		5.3	2.4	c	-	76	46		
18 Liverwort	274	208	b		5.5	1.8	c	-	117	103		
8 Liverwort									12	6		
8 Moss	246	395	ac		3.1	1.4	b	-	37	41		
1.5 Moss	132	284	a	-	2.5	1.0	a	-	60	73		
Wet season 2016					-			-	69	72		
above canopy	2084	517	d	0.000	7.0	1.8	d	0.000				
23 Liverwort	329	223	c		8.1	3.1	d	-	99	75		
18 Liverwort	289	188	c		6.0	1.7	c	-	76	39		
8 Liverwort									44	59		
8 Moss	44	88	b		3.7	1.9	b	-	44	53		
1.5 Moss	96	140	a	-	2.8	1.0	a	-	69	72		