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

Dear Professor Bahn,

we would like to thank you and the reviewers for the manuscript evaluation and the comments, which helped 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 you and 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. The figure and table numbers refer to the revised manuscript. Furthermore, some two supplemental files (*“Exemplary results for the percentiles 5 and 95”, “Exemplary results for the percentiles 1 and 99”*) are attached. In this revised version, Rodrigo Alves has been added to the authors’ list, as he has helped considerably with data analysis and improving the manuscript.

Sincerely,

Nina Löbs, on behalf of the co-authors.

Comments of the editor:

your manuscript has been re-assessed by two of the earlier reviewers, who both think that the manuscript does not live up to its potential concerning an assessment of the functioning of tropical epiphytic bryophytes in the Amazon. However, they also think that it should be in principle publishable because it provides new and useful microclimatic data with functional relevance. I am therefore inclined to accept our manuscript for publication in Biogeosciences, in case you manage to address the concerns the reviewers have raised in a satisfactory manner. Most importantly, reviewer #1 has had some serious doubts concerning the values you provide for water contents and thinks that there might have been an issue with your calculations. As good estimates of water contents are key to any functional interpretation it will be essential to follow up on this concern very thoroughly.

Author comments:

Thank you very much for the chance to improve and resubmit our manuscript once again! During the revision process, we carefully reinvestigated the calculations of the water content values once again, which is documented in the response letter and the supplementary material of the manuscript. We believe that we now identified the most appropriate method to determine the water content data, based on the electrical conductivity measurements and we carefully discuss the meaning and the limits of these results.

We feel the manuscript has improved a lot and each suggestion and comment has been addressed. We hope that this version will be suitable for publication in Biogeosciences.

Referee report #1

Submitted on 07 Nov 2019, Referee Maaike Bader

Referee comment general:

The new version of your manuscript, now with the adjusted title “Microclimatic conditions and water content fluctuations experienced by epiphytic bryophytes in an Amazonian rain forest” has improved a lot, in particular in the more cautious discussion of the results. I now have only one major problem with the results, and that is in the very unlikely water content values.

I appreciate it that you tried out the method I suggested, and I still think that method makes sense, but the results are not very convincing as they are. It does not make any sense that the liverworts in the canopy should have a constantly high water content. Also, it does not make sense that the bryophytes in the understorey should never reach WCs above about 400% (Table S1, Fig S8 – even if this is for 30-min averages, during rain events the mosses could stay at their maximum capacity for half an hour), if their maximum WC is about 1500% for Leucobryum and 1000% for Sematophyllum (your data in Fig S3 in the previous version).

In any case, there must still be something wrong with the calculation. Perhaps it would help to not take the absolute min and max mV signal ever measured by the sensors, but something like the 5% and 95% Quartiles, to avoid using spurious signals. Supporting the assumption that this has happened is that it does not make sense that any of the mosses and liverworts should go down to values as low as 0 or 1% WC - this is what one would reach in a good drying oven, not at >70% RH… So the real minimum WC should be higher. Also, there may be a meaning in the fact that the maximum electrical conductivity measured in the field was much higher than those measured during calibration for Leucobryum (Lm) and Sematophyllum (Ss) (Fig S3 of previous version). The result of this is that the new function used estimates much lower WC values than those estimated by the calibration curves. I agree that the calibration curves (not presented in this version of the paper as they were not used for the new WC calculations) were problematic due to the huge variability (especially for Symbiezidium, not so much for Lm). Still, they might be used to constrain the range of relationships between electrical conductivity and water contents that can be considered acceptable, and for Lm and Ss the current functions use would fall outside this range, with systematic underestimations of the water content. If the calibration curves have a meaning, I would expect electrical conductivity in the field to be usually between near-0 and 600 (Lm) or 300 (Ss). By plotting the histogram of the conductivity values it may be possible to identify a more realistic value corresponding to maximum moss wetness.

For Symbiezidium I suspect that the water content is, on the other hand, systematically overestimated. It seems rather impossible to me that a canopy bryophyte would maintain a WC of around 100% all the time. It would be really good if the quantitative translation of sensor output to water content can be managed, because the data do show that there is a signal in the data, e.g. by the strong response of at least some of the sensors to rain events. I think there are some interesting patterns in the data, in particular the diel fluctuation of the WC in the upper canopy, apparently following RH fluctuations. It does make sense that this diel fluctuation is largest at the upper two heights. So it is mainly the determination of the absolute WC that is problematic, not so much the fluctuations.

There may be a way to deal with this though. Apart from trying not using the absolute minimum and maximum ever measured but the 5% / 95% quartiles, you may also need to use the 30-minute averages, so as not to use the lower end of the short-term fluctuations as a minimum and upper end of those fluctuations as a maximum. Judging from Figure S4 those fluctuations may be a problem especially at 23 m, which could explain the high mean values there if you use the 5-min data for the calibration. I could imagine that after rain, they may also become more pronounced at e.g. 1.5 m. I might have to take back the recommendation to use 5-min values for the estimation of activity times, at least for WC.

A second point: I wonder how interesting it is, in the context of predicting activity of the mosses, to put emphasis on the seasonal patterns in the mean values of the climatic variables. What could be more interesting is to analyse the bryophyte activity patterns separately for the seasons.

Author comment:

Dear Maaike Bader, we would like to thank you for your critical and very constructive comments on our manuscript. We appreciate your feedback a lot!

Many thanks for your idea to calculate the quartiles in order to obtain more reliable water content values. For the correction/ limitation of the considered data range, we calculated three percentile options, i.e. 5 and 95%, 1 and 99%, and 0.1 and 99.9%, to eliminate potential outliers. The resulting data range for the different sensors and percentiles are listed in the *Table S3 (see below)*.

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

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

Additionally, the results obtained by utilization of all these percentiles are listed in the supplementary files ("*Exemplary results for the percentiles 5 and 95", "Exemplary results for the percentiles 1 and 99*", Percentiles 0.1 and 99.9 are presented in the revised *manuscript*"). In these supplementary files the translation from 'measured electrical conductivity' via 'by percentiles cleaned electrical conductivity' to 'calculated water content' can be seen in the first figure each.

After careful comparison and evaluation we decided to consider 0.1 % and 99.9 % percentiles, because the 99.9 % percentile already shows a large difference to the total data range (Max_total), which might be explained by outliers, while the steps to the next percentiles are not that big anymore and might present reasonable measurements. For an equal correction at both ends, we decided to also consider 0.1 % for the lower data range; however, there are not as extreme outliers as observed for the upper data range.

In addition, we also looked into the electrical conductivity data of the lab versus field data once again. As we see a large variation of EC-values for the different samples of one species and we couldn't use the exact samples of field measurements during lab calibrations, we believe that it is better to only use the maximum and minimum water content values from these lab measurements but not the electrical conductivity values or the form of the curve obtained in the lab. The minimum WC corresponds to the weight of the sample after drying at 40°C and 30 % relative humidity in order to use a realistic data range. As you can see in the table above, this minimum water content is ranging between 13 and 16% for the different species.

The water contents reached by the sample replicates during measurements in the laboratory are shown in an additional table *(Table S2, see below*). As you can see here, *Symbiezidium* consistently reached high water content values for all replicate samples.

Thus, we believe that the high water contents reached by the samples at the upper canopy levels and the relatively quick drying of the samples close to ground levels is not an artefact but a real feature, which is caused by the exact habitat occupied by these samples in the field. At 1.5 m height, *Sematophyllum subsimplex* and *Leucobryum martianum* grow on the vertical stem. During rain events they get wet, but after that they dry rather quickly again as the water effectively drains from the samples. At 18 and 23 m height, *Symbiezidium barbiflorum* grows on an inclined branch and on the upper side of a branch (*see Fig. S4*). Here, the samples keep increased water contents over longer time spans. This is a general pattern, which could already be observed in the original electrical conductivity values (see Fig. S7 in the revised *manuscript*). We explain this also in the manuscript on page 17 line22ff. and Page 21 line 17ff.

We also happily took up your suggestion to analyze the physiological activity during the different seasons. The results of these calculations are shown in *Fig. 4* of the main manuscript *(see below*), were we plotted the results for the wet and the dry season in a separate manner.

Author changes in the text:

P17 L22: "The high WC of the bryophyte samples in the canopy can be explained by the higher water holding capacity of the liverwort *Symbiezidium*, which dominated in the canopy, and by its growth on inclined or vertical stems, where water drainage is less effective as compared to the vertical stem at the lower two levels. The relevance of the water holding capacity for the water content of different bryophyte species has already been described in several other studies (Lakatos et al., 2006; Romero et al., 2006; Williams and Flanagan, 1996)."

P21 L17:" In the canopy, the dominating liverworts responded to the nightly increase of RH, which was not observed for the mosses in the understory. Thus, the relevant water source for bryophytes in the understory might be rain, while for the bryophytes in the canopy the nightly increase of the RH might be relevant for an activation of the physiological processes."

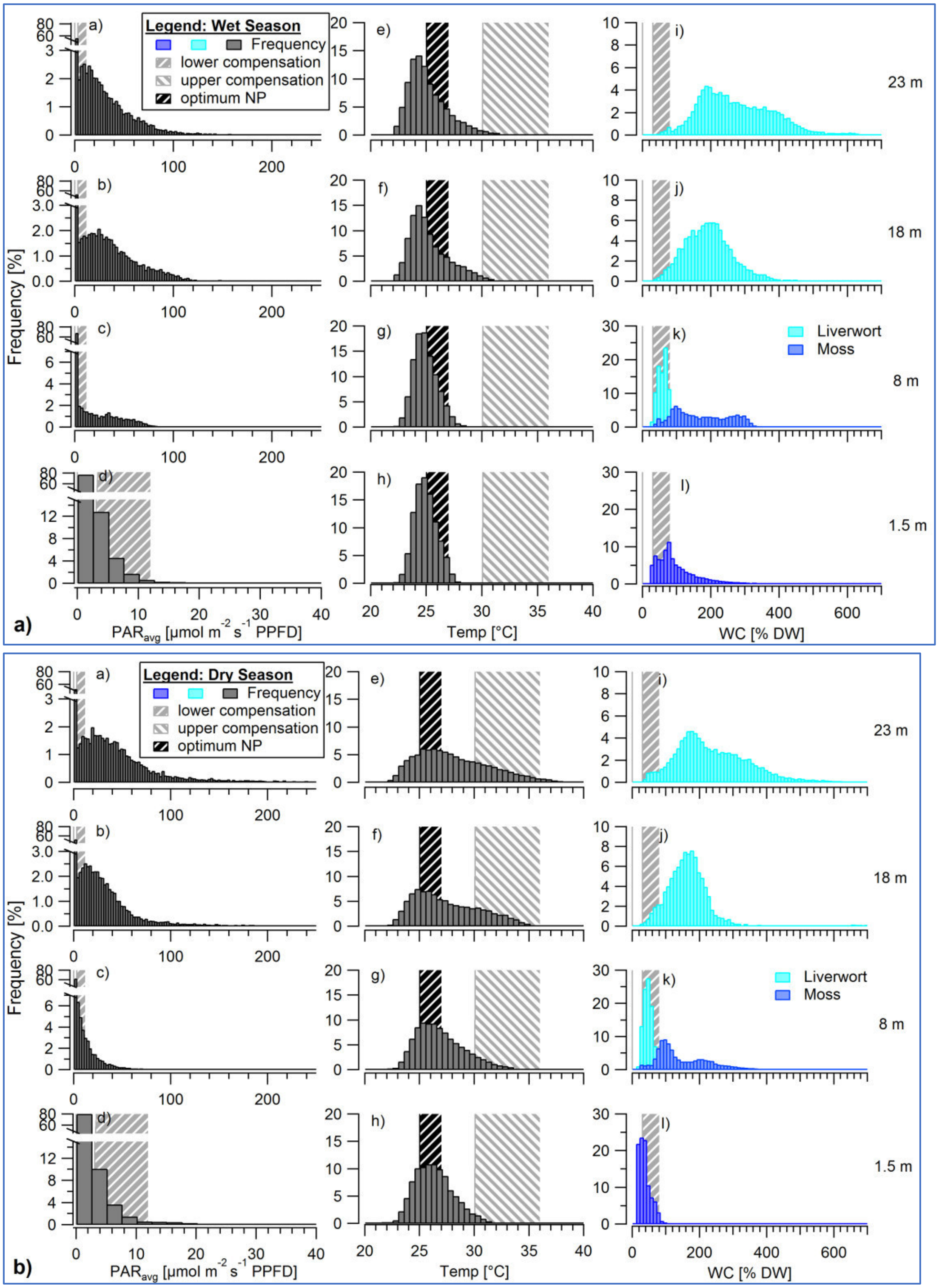

__Figure 4:__ Frequency of light (PAR$_{avg}$; a – d), temperature (Temp; e – h), and water content (WC; i – l) measured on top/within bryophytes at 1.5, 8, 18, and 23 m height within the canopy during (a) wet and (b) dry season. Calculation of the histograms based on 30-minute intervals. Shaded areas represent the ranges of lower compensation (PAR, WC), upper compensation (temperature), and temperature for optimum net photosynthesis (black shading). Value ranges are adopted from Lösch (1994) and Wagner et al., (2013) (Table S4). Bin sizes: PAR: 2.5 µmol m^{-2} s^{-1}; temperature: 0.5 °C; WC: 10 %.

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

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

Some smaller points:

Even if you do not use the calibration any more in this version, please do describe the fact that variability was high in these experiments, so that the uncertainty of the WC values is expected to be very high. Discuss why the calibration curves could not be used, so why the current approach was chosen. Also, on the positive side, you can describe how single measurement series showed a more or less linear relationship between mV and WC (except at very high WC, where the measurement tended to became saturated and mV did not longer change), justifying your linear approach in calculating WC from mV.

Author comment:

We added information on the calibration data in the text.

Author changes in the text:

P6 L1 30: "In a previous approach, calibration curves were established under controlled conditions, logging the electrical conductivity values and the corresponding weight/water content of samples of the different bryophyte species during drying (Weber et al. 2016). However, the variability of electrical conductivity values between samples and even at different spots within one sample turned out to be too large and thus this was not a feasible approach to calibrate the sensors. On the other hand, the electrical conductivity values decreased in a linear way with decreasing sample weight, demonstrating that a linear relationship between both factors could be assumed (except for water contents close to saturation). "

Referee comment:

It would be good to present the min and max WC values (from your calibration curves) to give readers more insight into the WC calculations.

Author comment:

The minimum and maximum WC values are presented above in Table S2, which is also included in the supplement.

Referee comment:

The discussion could present a stronger line in the points being made. As it is, some paragraphs seem a bit lost, rather than incorporated into a story. The story could, for example, be centered on the activity patterns, presenting the microclimatic data in that context. At the moment, context is missing a bit for some sections.

Author comment:

We worked on the discussion again and made sure that there is a logical structure and that there are no lost paragraphs. After this effort, we think that the discussion reads logically and smoothly.

Detailed suggestions:

Referee comment 1:

Abstract (p2), L16 I would not call the diel fluctuations in WC ´frequent wetting and drying events´ (although my expectation would indeed be that they would go through more than in the understorey, but form your data this is not obvious), how about calling them diel fluctuations? It looks like for your samples, the lower ones actually lived through more wetting and drying events as they responded to rainfall more directly / consistently (would be nice to quantify ´consistently´...). In any case, the WC calculations need to be revised so this sentence may still change, although the fluctuations will probably be little affected by the recalculation of the absolute values.

Author comment:

It is a good idea, we changed this accordingly.

Author changes in the text:

P2 L16: “Whereas bryophytes at higher levels were affected by diel fluctuations of the relative humidity, those close to the forest floor responded to rainfall more directly.”

Referee comment 2:

P2 L7-8 why the quotation marks?

Author comment:

Indeed, the quotation marks are not necessary and were deleted accordingly.

Referee comment 3:

P2 L21: measurements of CO2 gas exchange would be necessary, but this study is not a starting point for such measurements. Maybe change to “supported by measurements of CO2 gas exchange”

Author comment:

This is a good idea and the sentence was rewritten accordingly.

Author changes in the text

P 2 L20: “For further research in this field, these data may be combined with CO_2 gas exchange measurements, to investigate the role of bryophytes in various biosphere-atmosphere exchange processes, and could be a tool to understand the functioning of the epiphytic community in greater detail.”

Referee comment 4:

P2 L30 I do not understand the ´equally´ here

Author comment:

It indeed does not fit here and has been substituted by “also”.

P3 L1: “However, they are also affected by deforestation and increasing forest fragmentation…”

Referee comment 5:

P3 L13 Have been reported

Author comment:

We do not understand this comment, as this has been written by us.

Referee comment 6:

P3 L17 Clarify what ´It´ is

Author comment:

‘The Amazonian rain forest’. The sentence was rewritten for more clarity.

Referee comment 7:

P3 L25 The ´Thus´ does not fit well. You introduce ecosystem functions but present data on microclimate…

Author comment:

Many thanks for this comment, we rephrased the section for more clarity.

Author changes in the text:

P 3 L22: “There is a lack of information regarding the *microclimatic conditions of the habitats colonized by cryptogamic communities in the tropics.* 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.”

Referee comment 8:

P3 L29 variations *in* climatic conditions

Authors comment:

The word was changed accordingly.

Referee comment 9:

P4 L23 What exactly do you mean by the ´story structure´? Is this more than just the vertical structure?

Author comment:

With story structure we address the vertical structure including the different height zones of the trunk and the branches of the crown. Zones 1-4 correspond to the base (1), the lower and upper trunk (2 and 3), and the lower crown section (4).

Author changes in the text:

P4 L21 :” 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 *((i.e., at the base, the lower trunk, the upper trunk, and at the base of the crown*) used by Mota de Oliveira and ter Steege (2015), to investigate the variation within the story structure of the forest.”

Referee comment 10:

P5 L1 Why ´Generally´?

Author comment:

This word was deleted.

Referee comment 11:

P5 L10-11 not only….. and height.

Author comment:

Thank you for the comment. The word ‘height’ describes better, what we intent to express with this sentence.

Author changes in the text:

P5 L12: “Thus, also the orientation at the stem may influence the WC of the bryophyte communities, not only the species and the *height above ground*.”

Referee comment 12:

P5 L21 were not installed

Author comment:

This tense was changed accordingly.

Referee comment 13:

P5 L28-30 Did you check/correct for drifts in the measured light levels due to e.g. algal growth on the light sensors?

Author comment:

Thank you for the comment. Yes, we checked the light sensors regularly for algal growth and other stains and cleaned them accordingly.

Author change in the text:

P6 L9-10: During measurements, the light sensors were regularly checked for algal growth and cleaned accordingly.

Referee comment 14:

P6 L11 would the voltage not be proportional to the conductivity if the sensor pins did not have a fixed distance?

Author comment:

The voltage is proportional to the conductivity, but an alternating distance of the pins would result an alternation of the resistance. As the conductivity is the inverse resistance, it would require additional calculation steps to get the corresponding voltage from the measured conductivity. Thus, with the current calibration of the sensors, the values can easily be transferred from voltage into conductivity.

Authors change in the text:

P6 L10: “The WC sensor *has a fixed distance between the sensor pins, which ensures that in all sensors the resistance is equal. This guarantees* that the electric voltage, being the inverse resistance, is proportional to the electrical conductivity. “

Referee comment 15:

P6 L22-25 This calculation of the water content does not really need a formula or a citation. It is simply the water content expressed per dry mass.

Author comment:

This is correct. Nevertheless, we would like to keep the formula for clarity.

Referee comment 16:

P6 L27-30 Like explained above, I would try using not the absolute min and max but something like the 5% and 95% quartiles, or some other reasonable min and max based on a histogram of the mV signals.

Author comment:

Thank you for the comment. We calculated new values based on 0.1% and 99.9 % percentiles of the electrical signal and adapted the text accordingly.

Authors change in the text:

P7 L11: “As we got the impression that electrical conductivity values may contain some outliers in the upper data range, we reduced the electrical conductivity data by the uppermost and lowermost 0.1% of the data points (Tab. S3). Accordingly, the water content (WC) was calculated as follows:

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

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

Referee comment 17:

P6 L5 remove 8

Author comment: Done.

Referee comment 18:

P6 L6 were considered

Author comment:

The tense was changed accordingly.

Referee comment 19:

P6 L12-15 try using a parallel structure (why were some data collected, others measured and others assessed?

Author comment:

Thank you for the comment. We adapted the structure for more clarity.

Referee comment 20:

P6 L20 I am still not convinced the ´integration´ is what you mean here.

Author comment:

We guess that you refer to P7 L20, i.e. the calculation of the rainfall data. for this, we summed up (= integrated) the 5-minute measurements, as an averaging of the 30-minute-data would result in an underestimation. Thus, we are confident that an integration of the 5-minute values is the correct way to obtain the mean rainfall data per month.

Referee comment 21:

P8 L7 We have already shown that high respiration loss due to high temperatures are probably not so important, as respiration rates are adapted/acclimatized to the elevation at which bryophytes grow (Wagner et al 2013, Annals of Botany). This could already be acknowledged here. And also in P12 L3-4, and in P16 L12, rather than suggesting that there is still all reason to think that night T is important to then, surprise surprise, conclude that it is not..

Author comment:

Thank you for the comment. We considered the reference and the information regarding nighttime temperatures.

Authors change in the text:

P8 L14: ”*For tropical bryophytes along an altitudinal gradient in Panama it has been shown that respiration loss during night might not play the determining role for an overall positive net carbon* *balance,* as species acclimatized to elevated temperatures, *but that the restricted time for photosynthesis was a decisive factor (Wagner et al., 2013)."*

P18 L16: "Thus, the temperature did not seem to be a limiting factor for the physiological activity of epiphytic bryophytes in this environment (Fig. S9). Similarly, also Wagner and coauthors (Wagner et al., 2013) stated that the temperature likely was not a limiting factor for the overall carbon balance of the bryophytes investigated in a low- and highland rainforest in Panama. "

Referee comment 22:

P8 L15 WCs BELOW the WCP

Author comment:

Thank you for the comment. The word was changed accordingly.

Referee comment 23:

P8 L23 if light intensity is above and temperature below the compensation point

Author comment:

In this case we are referring to the "upper" temperature compensation point, which indicates overall respiration values. Thus, we think that the sentence is correct.

Referee comment 24:

P9 L16-19 I would suggest to make clear here already that these measurements may be strongly influenced by local canopy cover, thus not necessarily reflecting the conditions for that stratus of the forest in general, and should therefore be taken with caution.

Author comment:

Thank you for the comment. We included a new sentence for more clarity.

Authors change in the text:

P9 L25:" However, the light conditions observed at one individual tree are strongly influenced by its canopy structure and foliation and thus could not be considered as data representative for the canopy in general."

Referee comment 25:

P9 L24-26 why is this interesting?

Author comment:

The comparison of the monthly temperature has been deleted, as there are no major differences.

Referee comment 26:

P9 L27 similar patterns to what?

Author comment:

The bryophytes water content showed a similar pattern compared to the increase and decrease of the values of rain and RH. The sentences was rewritten.

Authors change in the text:

P 10 L19: “*Over the course of the years, the monthly WCs of epiphytic bryophytes showed similar patterns corresponding to the increasing and decreasing values of rain and RH.* “

Referee comment 27:

P10 L2 RH where?

Author comment:

The RH was measured in 26 m height. This information is provided in the material and methods section.

Referee comment 28:

P10 L3 I really do not believe this result (RH highest at 23 m)

Author comment:

I guess you mean ‘WC’ instead of ‘RH’?! In the very beginning of the analysis of the data we also expected WC values to be the highest in the understory and the lowest in the canopy. However, we consistently obtained higher electrical conductivity values for the canopy, suggesting higher WC values for these height levels. Furthermore, also during the lab measurements the liverworts showed higher maximum water contents as compared to the mosses collected at lower levels. Thus, we meanwhile believe that the liverworts frequently show higher WC values than the mosses. This is supported by the fact that the mosses at the low levels grow vertically along the stem whereas the liverworts in the upper levels grow on inclined or even vertical branches. Thus, drainage at the lower levels tends to happen much faster than at the upper levels. In addition, the thickness/density of the cushion might play a crucial role. As the cushions are denser at the upper levels, they may hold the water for longer times as compared to the fragile and loose thalli growing at the lower levels. Thus, we believe that besides temperature and RH also other factors, like the exact epiphytic position (vertical or horizontal growth) and the cushion morphology influence the water content of the sample. Nevertheless, one has to keep in mind that measurements on other trees might show a different pattern of bryophytes WCs and metabolic activity.

Referee comment 29:

P10 L8-9 Suggestion to not talk about this result as ´showing high WC´ but rather as ´showing high conductivity, but this could not be related to the WC because of reinstallation… Or if you have enough data you could adjust the function by taking a new max (95%) and min (5%) mV signal.

Author comment:

These are indeed very good suggestions. As we do not have enough data for a recalibration of the data after repositioning of the sensors, we prefer the first suggestion made by you.

Authors change in the text:

P11 L2: "*Furthermore, the liverworts at 8, 18, and 23 m height showed particularly high conductivity values in November and December 2016, which might be caused by a previously required reinstallation. Consequently, the calculated WC values of the reinstalled sensors need to be considered with special care, as they cannot be directly compared to the values prior to reinstallation."*

Referee comment 30:

P10 L21 Temperatures showed (not reflected)

Author comment: We changed the word accordingly.

Referee comment 31:

P10 L28 Any way of knowing whether the fog touched the canopy?

Author comment:

Thank you for the comment. To our experience, fog defined as visibility below 2000 m also occurs within the forest and not only above.

Author change in the text:

P12 L 14: According to our observations, fog observed above the canopy normally also occurred (at least to some extent) within the forest.

Referee comment 32:

P11 L2-3 This is a very interesting observation. It would be great if you could show (calculate) how consistent this response is. The examples shown in Fig S7 are not necessarily convincing, given all the fluctuations in the WC…

Author comment:

Unfortunately, a calculation of the response of the water content sensors upon fog events was not very successful, due to the large variability in the water content data before and during fog events. Additionally, fog frequently occurred after rain events and the wetting of the bryophyte samples by rain was often dominating the whole process. Consequently, up to now we couldn't use our data to calculate an effect of fog on the water content of the bryophytes. Up to now, we could only show some sporadic events where the water contents increased upon the event of fog. Thus, we reformulated the sentence accordingly.

Author changes in the text:

P12 L18: “Nightly fog might serve as an additional source of water, as in some cases the WC of the bryophyte communities increased upon fog events (Fig. S8).”

Referee comment 33:

P11 L10-11 these amplitudes are caused by fluctuations at different scales (rain events at 1.5 m, diel humidity fluctuations at 23-m), therefore I am not convinced that it is useful to compare them. Also, this sentence seems repeated in L 27-30.

Author comment:

Thank you for the comment. We agree with you, that the increasing water contents in the understory and in the canopy seem to be caused by different wetting and drying patterns. We now address these in a better way and discuss them in the discussion section.

The repeated sentences in L27-30 has been deleted, accordingly.

Author changes in the text:

P11 L21: “While the microclimatic temperature and light conditions within and on top of the epiphytic bryophyte communities followed the above-canopy conditions, modified by canopy shading, the WC of bryophytes did not present a clear pattern (Fig. 3).”

Referee comment 34:

P11 L21 what ´mean´ are your referring to?

Author comment:

With ‘mean’ it was intended to express that this value is the average of all sensors and per season. We agree that it can be deleted.

Referee comment 35:

P11 L9 make clear here whether ´reported time´ considers 24-h or only daytime

Author comment:

We are referring to 24-h base.

Author changes in the text:

P14 L2: “In the understory (1.5 m) the lower light compensation point (LCP_l), ranging between 3 and 12 µmol m^{-2} s^{-1} (Lösch et al., 1994), was exceeded during 2-19 % of the time during the wet season and during 4-16 % of the time during the dry season, whereas at the two uppermost height levels the bryophytes exceeded these values during 34-47 % of the time during both seasons (Table 3).”

Referee comment 36:

P12 L12 Instead of ´microclimatic temperatures´ I would use ´temperatures inside the moss stands´

Author comment:

Thank you for the comment. The sentence was adapted accordingly.

Referee comment 37:

P13 Because of the reasons described in L12-13 and L17-18, I would not present the differences in light levels between seasons (L6-8) in that context, though it is probably worth discussing the artefacts because of the use of these data for estimating activity patterns.

Author comment:

Thank you for the comment. This is a good point and we revised the result and discussion part according to the focus on the canopy structure mentioned by you.

Author changes in the text:

P 15 L8: “Over the course of two years, the monthly averages of above-canopy light conditions (PAR_{avg}) were rather stable (Table S4). Within the canopy, the monthly PAR_{avg} values at 23 m height tended to be higher during the dry seasons, whereas patterns were less clear at 18 and 8 m height and there was hardly any seasonal variation at 1.5 m height. This was most probably an effect of the canopy structure, cushion orientation, and shading.”

Referee comment 38:

P13 L31-34 What is the interest in knowing the difference in mean temperature, which is physiologically meaningless..?

Author comment:

We think that this information is of overall interest, although it might not have a direct effect on ecophysiological processes. As it also compares nicely to other studies cited in that context, we would prefer to keep this information in the text.

Referee comment 39:

P14 L1 This sentence can be removed

Author comment:

We agree and deleted this sentence.

Referee comment 40:

P14 L5-8 Example of a ´lost´ paragraph with no clear function in the story.

Author comment:

Thank you for the comment. The paragraph was deleted.

Referee comment 41:

P14 L9 it is not the response that changes between seasons, but the conditions.

Author comment:

Thank you for the comment, we changed the sentences accordingly.

Authors change in the text:

P16 L17: ”As expected, the moisture conditions, including rain, fog, and RH, differed between seasons, resulting in different WC patterns of bryophytes.”

Referee comment 42:

P15 L4 What is ´stepwise´ about this drying?

Author comment:

We intended to explain that the drying of the mosses in the understory is rather slow and takes longer compared to the liverworts in the canopy. The expression “gradually” might describe this pattern in a more adequate manner.

Authors change in the text:

P17 L13: “The WC of bryophytes in the understory responded clearly to rain events during the wet season, and subsequently water was lost *gradually*, with bryophytes staying wet and active over prolonged time spans (Fig. 2, Fig. S6).”

Referee comment 43:

P15 L5-7 You know what the water holding capacity (WHC) of your species is, and you even have information about their drying speed (both from your calibration curves), so there is no need to speculate here. Unfortunately, I think the WHCs of your species do not explain the pattern at all, if anything, they would cause a reverse pattern, with *Leucobryum* staying moist longer than *Symbiezidium*…

Author comment:

A main result of our lab calibration was that the liverwort *Symbiezidium,* which is dominating in the canopy, reached the highest water content values and thus has the highest WHC compared to the other three moss species (Tab. S1, S2). Thus, we think that these data rather nicely reflect the patterns that we observe in the field, although they are not in line with the results that one might expect in the beginning. As described above, we think that the high water contents in the canopy are caused by the higher WHC of the canopy species and the microhabitat where the samples grow (inclined or horizontal substrate as compared to vertical substrate at lower stem levels).

Authors change in the text

P17 L17: "The high WC of the bryophyte samples in the canopy can be explained by the higher water holding capacity of the liverwort *Symbiezidium*, which dominated in the canopy, and by its growth on inclined or vertical stems, where water drainage is less effective as compared to the vertical stem at the lower two levels. The relevance of the water holding capacity for the water content of different bryophyte species has already been described in several other studies (Lakatos et al., 2006; Romero et al., 2006; Williams and Flanagan, 1996)."

Referee comment 44:

P15 L16 I agree with this, but it could be elaborated upon a bit more, and I think you need to aim at making these values indeed approximate but no longer biased.

Author comment:

Thanks for the comment. We extended the discussion about the sensor position.

Authors change in the text:

P17 L31: "*Furthermore, also the density and thickness of the investigated bryophyte sample is of high relevance. These are features, which are closely linked to the species, but also influenced by abiotic habitat conditions (Fig. S4).*"

Referee comment 45:

P15 L21-22 It is not correct to equal acclimation processes to intraspecific variation. Intraspecific variation can also be a result of adaptation, see e.g. Marks et al 2019. The references cited here also do not refer to acclimation.

Author comment:

Authors change in the text:

P18 L4:" 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 intraspecific variability*, the performance of species under differing microenvironmental conditions can also be modulated by *adaption processes, driven by environmental exposure, genetic variation among populations, and* *plasticity as,* e.g., shown for bryophytes and lichens (Cornelissen et al., 2007; Marks et al., 2019; Pardow et al., 2010)."

Referee comment 46:

P15 L24-25 What is the function of this sentence? It breaks up the flow of the story.

Author comment:

Yes, indeed, this sentence does not fit here and thus was removed.

Referee comment 47:

P16 L1-4 reacting rapidly and efficiently to light flecks is not at all the same as being efficient at low light levels, this sentence thus does not make much sense: P16 first paragraph. The ´so what´ of this paragraph is unclear.

Author comment:

Thank you for the comment. We are aware of the fact that these two things are not the same and rewrote the paragraph for more clarity.

Author changes in the text:

P18 L25: "As high light conditions mainly occur as short light flecks in the understory, the organisms need to react rapidly and efficiently to changing light conditions to reach overall positive net photosynthesis rates*. Furthermore,* understory mosses and lichens 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)*."*

Referee comment 48:

P16 L7-8 is photosynthesis not a metabolic process?

Author comment:

Yes, the photosynthesis is a metabolic process. We intended to stress that the respiration is more temperature sensitive than the photosynthesis. We altered the sentences to improve clarity.

Author changes in the text:

P19 L3: "The temperature regulates the overall velocity of metabolic processes*. While it has a strong impact on the respiration, the photosynthetic light reaction is by far less affected by it* (Elbert et al., 2012; Green and Proctor, 2016; Lange et al., 1998)."

Referee comment 49:

P16 L17 I do not agree that this has been shown at all, I think this sentence and those that follow will be removed after revising the WC method.

Author comment:

As described above, we spent large amounts of time to analyze and re-investigate the electrical conductivity data and the calibration process once again. After this careful re-iteration, we are very confident that the organisms in the canopy indeed have higher average WC values as compared to the ones in the understory. This is most probably caused by 1. The differing microhabitat, with samples in the canopy growing on inclined or even horizontal branches as compared to the understory samples growing on the vertical stem, and 2. The denser cushions of samples growing in the canopy as compared to those in the understory. We are fully aware of the fact, that the abiotic conditions alone (i.e. temperature and RH) would suggest a very different setup.

Author changes in the text:

P19 L14: "Unexpectedly, the WC of bryophytes has been shown to be higher in the canopy than in the understory. In the understory, the WCP was surpassed during 4-54 % of the time during the dry season and during 53-95 % of the time during the wet season, whereas at 18 and 23 m it was surpassed during 93 – 100 % of the time, without a clear difference between the seasons. In the understory, the WC of cryptogams seemed to be predominantly regulated by rain events, whereas in the canopy, the samples stayed relatively homogeneously wet over long time spans (Fig. 2). This was unexpected at first sight, as one would expect them to dry quickly at the higher canopy levels. However, as the samples at the two upper canopy levels grew "sitting on top" of nearly horizontal branches, they presumably could store the water over longer time spans as compared to the bryophytes at the lower trunk section, which grew on the vertical stem. Additionally, the liverwort community in the canopy seemed to form thicker and denser cushions, which could store water more effectively as compared to the mosses in the understory, which occurred in thin and rather loose cushions (Fig. S4)."

Referee comment 50:

P16 L24-25 Really? What would be the mechanisms for this?

Author comment:

We are sorry, that we mixed up vertical and horizontal in this sentence. The samples at the upper two tree levels grew on top of inclined or horizontal branches, while the bryophytes at the two lowest stem sections grew on the vertical trunk. Thus, the samples "sitting on top" of a branch might keep the water for longer time spans, while these at the vertical stem might drain more quickly.

Author changes in the text:

P19 L22: "This was unexpected at first sight, as one would expect them to dry quickly at the higher canopy levels. However, as the samples at the two upper canopy levels grew "sitting on top" of nearly horizontal branches, they presumably could store the water over longer time spans as compared to the bryophytes at the lower trunk section, which grew on the vertical stem. Additionally, the liverwort community in the canopy seemed to form thicker and denser cushions, which could store water more effectively as compared to the mosses in the understory, which occurred in thin and rather loose cushions (Fig. S4)."

Referee comment 51:

P17 L3 was "exceeded" during.. Except that it was not ;-)

Author comment:

Thank you very much for the comment. We now use the expression, that compensation points were "surpassed", as presented in the two text sections cited above.

Referee comment 52:

P17 L13 I agree! Except from questioning the generality of the published compensation points, this would also be a good place to critically evaluate your microclimatic data!

Author comment:

We recalculated the conditions and time ranges of physiological activity and all the sections in the text were adapted according to the new results.

Author changes in the text:

P20 L30: "The large discrepancy between the time ranges for NP and DR calculated for the bryophytes in the canopy and the understory gives reason to expect the LCP_l *and the WCP to be at the lower end of the range (3 µmol* m^{-2} s^{-1}*, 30 %) for the bryophytes at the lowest height level and to be at the upper end of the range (12 µmol* m^{-2} s^{-1}*, 80 %) for the bryophytes at the two uppermost height levels. For other habitats,* LCP_l*s as low as 1 µmol* m^{-2} s^{-1} *have been defined for lichens (Green et al., 1991), and thus it could be possible that the bryophyte communities in the understory exhibit similarly low* LCP_l *values. However, one also has to keep in mind that the uncertainty inherent in the microclimatic data directly impacts the calculated physiological patterns."*

Referee comment 53:

P18 L1-2 revise after recalculations. And I would rise the diurnal variation in WC in the upper levels to the conclusion section. This could be very relevant, but this depends on the exact WC values and the exact WCPs, neither of which, unfortunately, we know…

Author comment:

All the paragraphs dealing with the WC and the estimated NP and DR have been revised after the recalculation of the WC. The diurnal characteristics of canopy samples, as an effect of the nightly increase of RH is now addressed at more detail in the conclusions.

Author changes in the text:

P21 L23: "In contrast to that, the WC of the bryophytes at higher levels remains high over most of the time, probably caused by the bryophyte morphology and also their growth habitat on top of inclined or horizontal branches. In the canopy, the dominating liverworts responded to the nightly increase of RH, which was not observed for the mosses in the understory. Thus, the relevant water source for bryophytes in the understory might be rain, while for the bryophytes in the canopy the nightly increase of the RH might be relevant for an activation of the physiological processes."

Referee comment 54:

P18 L4 … minor variation relative to the physiological tolerances of the mosses, as far as these are known, …

Author comment:

Thank you for the comment. The sentence was rewritten for clarity.

Tables

Referee comment 55:

Table 3 It is not totally clear what is meant by ´are reached´. It looks like you mean ´exceeded´, which has the problem that, depending whether it is a lower or upper CP, the shown values can be the time net photosynthesis could be positive (LCP, WCP) or the time that it could not (TCP)… While for Topt it is not so clear.

Author comment:

The table was reorganized for more clarity. We moved information of the table into the caption. And yes, the time ranges when CP of water, temperature and light are exceeded are given. Additionally, a table presenting the wet season and one presenting the dry season is shown in the revised version.

Author changes in the text:

New Tables for Dry and Wet season

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

a) Wet season

Height	**Division**	**LCP_l**	**$T_{opt\ range}$**	**TCP**	**WCP**	**NP**	**DR**
		≥ 3-12	24.0-27.0	≥ 30.0-36.0	≥ 30-80		
		µmol m^{-2} s^{-1}	**° C**	**° C**	**% DW**		
[m]	**L/M**	**Time fraction when cardinal points are reached/exceeded [% of time]**					
23	L	34-43	4-54	0-3	53-100	27-38	62-66
18	L	40-46	4-55	0-2	20-100	32-43	56-57
8	L	25-31	2-74	0	1-98	5-40	11-56
8	M				25-100	26-36	54-63
1.5	M	2-19	2-77	0	9-95	1-15	53-79

b) Dry season

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

Referee comment 56:

Table3: why a column for showing the ´conditions´ which are the same everywhere?

Author comment:

This column showing the conditions was deleted. A prior version of this column presented different conditions for the CP at the different height levels, but in the meanwhile this was unified for all height levels.

Referee comment 57:

P29 L4 occur are listed

Author comment: The tense was changed accordingly.

Figures

Referee comment 58:

P30 L5 remove ´epiphytic´ or ´the´

Author comment: Done.

Referee comment 59:

Fig 2: it is hard to see all the information here, could it be printed larger?

Author comment: The figure is printed larger, now.

Referee comment 60:

Fig 3 match order in caption to order in graph.

Author comment: Done.

Referee comment 61:

Fig 3b: The green for WC at 18m is a different colour than the rest

Author comment: Adjusted.

Supplementary material

Referee comment 62:

Fig S4 This figure is cool it shows nicely how the T at 23m is most variable and mostly higher than at lower heights. The model for the 23-m data does not seem to fit well, though this is hard to see well because of the superposition of the points… Maybe also provide some panels with the data and models per height separately?

Author comment:

Thank you for the comment. The figure (now it is Fig. S5) was changed, since the time scales of the 5-minute and the 30-minute data (averages) sets were not aligning well. There was a shift of 15 minutes, which now has been aligned. We also stretched the y-axis for clarity.

Author changes in the text

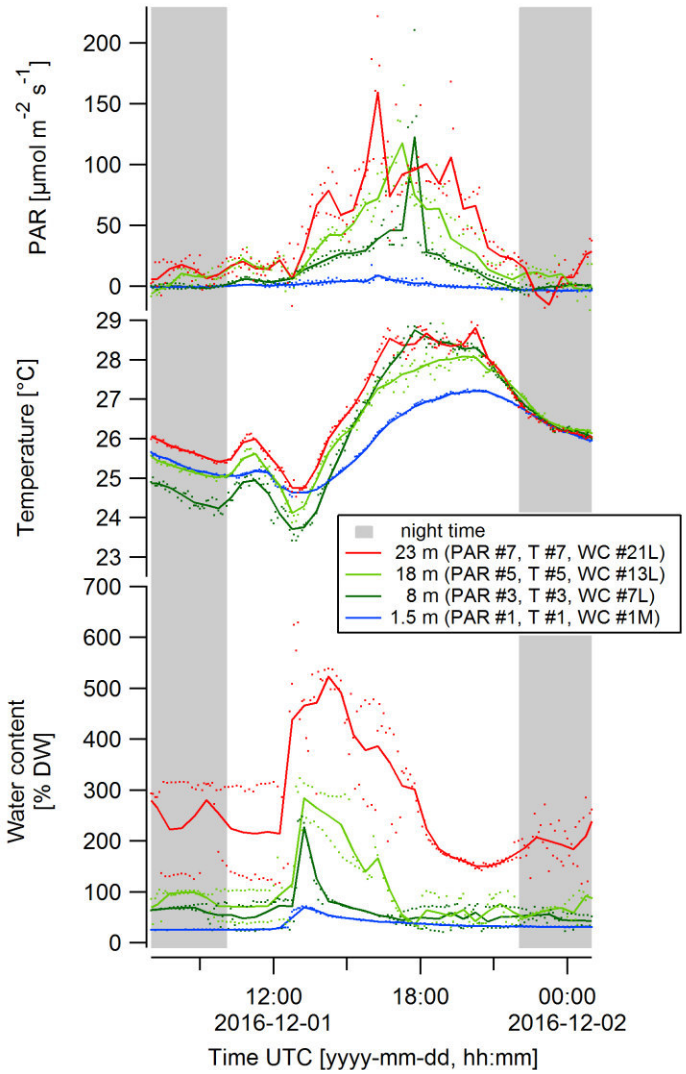

Figure S5: Comparison of 5-minute (dots) and 30-minute (lines) averages of exemplary sensors at each height level over a period of approx. one day in December 2016.

Referee comment 63:

& Digits in R2…, Above canopy AT 26 m

Author comment: Adjusted.

Referee comment 64:

Table S1 The 0 and 1% minimum WC values are probably just values due to some unexplained fluctuations in the sensors, so I would not report these extremes but rather the 5% quartile or something like that. The same goes for the ´maximum´.

Author comment:

The minimum and maximum data have been recalculated after exclusion of the 0.1 and 99.9 % percentiles.

Author change in the text

Table S1: *Height of installation, minimum and maximum values of the individual sensors of the microclimate station measuring water content, temperature, and light. For the water content sensors, also the bryophyte species are given and for the data set the 0.1 and 99.9 % percentiles were considered and not the absolute minimum/maximum values. Based on 30-minute averages.*

Water content	**Height**	**WC [% DW]**		
	[m]	Min (0.1%)	Max (99.9 %)	**Bryophyte species**
Sensor 01	1.5	14	762	*Sematophyllum subsimplex*
Sensor 02	1.5	14	761	*Sematophyllum subsimplex*
Sensor 03	1.5	13	761	*Sematophyllum subsimplex*
Sensor 04	1.5	15	1368	*Leucobryum martianum*
Sensor 05	1.5	13	760	*Sematophyllum subsimplex*
Sensor 06	1.5	17	750	*Sematophyllum subsimplex*
Sensor 07	8	16	1647	*Symbiezidium barbiflorum*
Sensor 08	8	15	1311	*Octoblepharum cocuiense*
Sensor 09	8	15	1302	*Octoblepharum cocuiense*
Sensor 10	8	16	1315	*Octoblepharum cocuiense*
Sensor 11	8	17	1649	*Symbiezidium barbiflorum*
Sensor 12	8	17	1639	*Symbiezidium barbiflorum*
Sensor 13	18	19	1657	*Symbiezidium barbiflorum*
Sensor 14	18	21	1576	*Symbiezidium barbiflorum*
Sensor 15	18	20	1637	*Symbiezidium barbiflorum*
Sensor 16	18	20	1626	*Symbiezidium barbiflorum*
Sensor 17	18	18	1655	*Symbiezidium barbiflorum*
Sensor 18	18	17	1618	*Symbiezidium barbiflorum*
Sensor 19	23	22	1598	*Symbiezidium barbiflorum*
Sensor 20	23			*Symbiezidium barbiflorum*
Sensor 21	23	22	1484	*Symbiezidium barbiflorum*
Sensor 22	23	22	1592	*Symbiezidium barbiflorum*
Sensor 23	23	29	1653	*Symbiezidium barbiflorum*
Sensor 24	23	17	1654	*Symbiezidium barbiflorum*

Temperature	**Height**	**Temperature [°C]**	
	[m]	**min**	**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	**max**
Sensor 01	1.5	0	634
Sensor 02	8	0	569
Sensor 03	8	0	1121
Sensor 04	18	0	525
Sensor 05	18	0	615
Sensor 06	23	0	654
Sensor 07	23	0	767

Referee comment 65:

Table S3 Explain what low and high mean.

Author comment:

(Now Table S5) The expression should explain the “range of values”. The table was changed for clarity.

Author change in the text:

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

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

Referee comment 66:

Table S7 Is showing PARmin really necessary?

Author comment:

No, but it was presented due to the consistency of the table structure. It's not shown anymore in the revised version.

Referee Report #2

Submitted on 12 Nov 2019, Anonymous Referee #3

Dear Editor and authors

I have checked the rebuttal provided by Löbs et al. regarding the manuscript "Microclimatic conditions and water content fluctuations experienced by epiphytic bryophytes in an Amazonian rain forest" submitted to Biogeosciences.

My general opinion after reading the explanations provided and changes made is that authors are losing a very nice chance for publishing a top reference paper regarding bryophytes functional performance in tropical regions. Authors state that moving samples to the lab for gas exchange experiments could damage the physiological performance due to the exposition to dryness necessary for samples packing and transportation. This could be true for samples used to be always wet in the field, but I bet that many others not following these patterns could show values close to maximum after an adequate revitalization period under controlled conditions in the lab similar to those occurring in the field. I wonder if there is any paper or papers available with tropical bryophytes being measured in the lab in order to help in the methodological approach to solve this potential problem. Anyway, a solution to this can be to perform gas exchange experiments in the field. If authors are going to do this in the future extensively, a first approach could be done in this paper just to double check predictions made. Even accepting that gas exchange is a next step in this research line and has no place in this first manuscript, I think that at least some chlorophyll a fluorescence measurements could have been done during some representative climatic conditions in order to have a rough idea about what happens in relation with WC and microclimate when real metabolic activity is being considered. This is not difficult to get and improves the manuscript substantially because it provides some reference points to metabolic activity assumptions. This extra measurements would be necessary only if extrapolation to functional performance are between the objectives of the research, the paper stands by itself with the microclimatic approach due to the novelty of the data.

As it is now, this research provides new and useful microclimatic data for tropical epiphytic cryptogamic covers, but extrapolations to functional performance with current data are very risky and should be kept to minimum and always highlighting clearly the caution linked to those assumptions. My point of view is not to block the publication of the manuscript because there are no similar data sets available in the literature. I really expect to see published a second part with real functional measurements that could close this interesting initiative despite of thinking that both objectives could be accomplished in one manuscript

Author comment:

Many thanks for the comment and the thoughtfulness. Unfortunately, due to time and manpower constraints it is not possible to include CO_2 gas exchange or chlorophyll fluorescence measurements in the current manuscript. However, CO_2 gas exchange measurements are planned as a next step following the current manuscript. Thus, for now, we keep the estimations for the physiological activity (NP and DR) at a minimum and we take great care to discuss these results in a very careful way. We also stress, that our results do not allow a generalization to the whole bryophyte community or even forest type, but they should be considered as a first rough result of these long-term measurements on the microenvironmental conditions.

Referee comment:

I would like to mention some points that are still unclear to me :

- In the rebuttal letter, authors mention that "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 CO2 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" This sounds to a likely alternative to real measurements but please state much more clearly in the text which are the sources of this information, which species were used at those papers (Lösch et at 1994 and Wagner et al. 2013), which accurate environmental conditions and habitats were the species used by those authors facing….In summary, all the functional part of the manuscript relies on this few measurements made by the authors mentioned, so I would give more emphasis to this fact in the introduction and, especially, in the final part of the discussion (the info is included partially in the results section, but I think that more details are necessary).

Author comment:

Many thanks for your comment. We now included more information on the organisms and study sites used in the studies, where the compensation points have been determined that were used by us for the physiological activity estimations.

Author changes in the text:

P9 L1: "The lower light compensation point (LCP_l) represents the minimum light intensity that allows a positive primary production; it ranges between ~ 3 and ~ 12 µmol m^{-2} s^{-1} for bryophytes (based on measurements of *Ectropothecicum* cf. *perrotii, Frullania* spec, *Neckera* spec., *Plagiochila divergens, Plagiochila squamulosa, Porothamnium stipiatum, Porotrichum molliculum, Racopilum tomentosum, Radula boryana, Rhizogonium spiniforme)* occurring in African tropical lowland rain forests *(Lösch et al., 1994). The epiphytic bryophytes grew in an upper lowland rain forest in the Kahuzi-Biega National Park (Zaire) at about 800 m a. s. l.. Microclimatic conditions inside the forest were similar to the conditions at the ATTO site, as RH ranged around 60-70 % during sunny days and temperatures remained above 20 °C during night and day."*

P9 L11 :" With regard to temperature, a range for optimum NP (T_{opt}) and an upper compensation point, where NP equals DR (TCP) can be defined. For tropical bryophytes *(i.e., the species Octoblepharum pulvinatum, Orthostichopsis tetragona, Plagiochila sp. 1, Stictolejeunea squamata, Symbiezidium spp., Zelometeorium patulum)* T_{opt} ranges between 24 and 27 °C and TCP ranges between 30 and 36 °C as described by Wagner and coauthors (Wagner et al., 2013). For long-term survival and growth, the bryophytes need to be predominantly exposed to temperatures below the upper compensation point, at least under humid conditions. 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). *The measurements performed by Wagner et al. (2013) were conducted at a study site (BT) in* *a lowland rainforest in Western Panama in the Bocas del Toro archipelago, located approximately at sea level. The mean temperature was 25 °C (26 °C during day, 24 °C during night), thus slightly warmer than the temperatures measured at ATTO. With 3,300 mm a^{-1} rain, BT is in a similar range as the ATTO site (2,540 m^{-1}). "*

Referee comment:

- If I have understood ok, authors have removed the statistical analyses provided in the first version of the manuscript. If this is correct, I would like to know why has this been done and implications of this over the interpretation of the data sets.

Author comment:

Thank you for this comment. Indeed, the statistical analyses have been removed in the revised version of the manuscript. This decision was made, due to pseudo-replicates, which do not allow a comparison between years (all parameters, expect for the water content, are measured by 1 or 2 sensors per height level) and due to the vague character of the calculated water content.

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

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Abstract. In the Amazonian rain forest, major parts of trees and shrubs are covered by epiphytic cryptogams of great taxonomic variety, but their relevance in biosphere-atmosphere exchange, climate processes, and nutrient cycling are largely unknown. As cryptogams are poikilohydric organisms, they are physiologically active only under moist conditions. Thus, information on their water content, as well as temperature~~,~~ and light conditions experienced by them are essential to analyze their impact on local, regional, and even global biogeochemical processes. In this study, we present 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~~ 84 % of the time. Temperatures showed only minor variations throughout the year with higher values and larger height-dependent differences during the dry season. The indirectly assessed water contents of bryophytes varied depending on precipitation, air humidity, and bryophyte type. Whereas bryophytes at ~~higher levels~~the canopy were affected by ~~frequent wetting and drying events~~ diel fluctuations of the relative humidity, those close to the forest floor mainly responded to rainfall ~~remained~~patterns~~ 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. For further research in this field, t~~T~~hese data may be ~~used as a starting~~ ~~point~~combined with CO_2 gas exchange measurements,~~,~~ 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.

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 also ~~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~~ The Amazonian rain forest has been described to play important roles in the water cycle, as well as ~~for~~ in 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 environmental changes will still ensure its ecological services as the “green lung” and carbon sink of planet Earth (Soepadmo, 1993).

Studies in temperate zones address the importance of cryptogamic communities for the ecosystem (Gimeno et al., 2017; Rastogi et al., 2018), but for the tropical area, only few reports can be found in the literature. There is a lack of information regarding the ~~functioning~~microclimatic conditions of the habitats colonized~~ of such~~ by cryptogamic communities in ~~an environment with an almost constant high relative humidity and temperature range~~the tropics. 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 bryophyte~~s~~ communities along a vertical gradient and an estimation of their activity patterns in response to~~ annual and~~ seasonal variations ~~of~~ in climatic conditions.

2 Material and Methods

2.1 Study site

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

2.2 Microclimatic conditions within epiphytic habitat

The parameters temperature and light within/on top of the bryophytes and their WC were measured with a microclimate station installed in September 2014 (Fig. S1). The sensors were placed along a vertical gradient at ~ 1.5, 8, 18, and 23 m above the ground, corresponding to the zones 1 to 4 (i.e., at the base, the— lower trunk, the— upper trunk, and at the— base of the crown) used by Mota de Oliveira and ter Steege (2015), to investigate the variation within the story structure of the forest. At each height level, six WC, two temperature, and two light sensors (except for 1.5 m with only one light sensor) were installed in/on top of different bryophyte communities located on an approximately 26 m high tree (Fig. S2, Table S1). It needs to be mentioned, that not only one single species was measured by one sensor, but usually several bryophyte species and also other cryptogams, such as lichenized and non-lichenized fungi and algae, as well as heterotrophic fungi, bacteria and archaea, which grow together forming a cryptogamic community. Thus, the organisms mentioned throughout this paper were the dominating but not solitarily living species. The restriction of the measurements to one individual tree needs to be considered, as a complete independence of the replicate sensors could not be assured. However, due to the large effort of such an installation within the rain forest, it was not possible to equip more trees with additional instruments. Thus, the data obtained from the measurements on this individual tree should be considered as exemplary. ~~Generally, t~~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, S2). 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~~ horizontal branch. Thus, also the orientation at the stem may influence the WC of the bryophyte communities, not only the species and the ~~canopy structure~~height above ground. Furthermore, sample properties as their thickness and density might play a relevant role for ~~its~~their WC, as samples ~~in~~at 1.5 m height tended to be more loose and thinner as compared to the ones at the upper height levels (Fig. S4). Since the installation, automatic measurements at 5-minute intervals were taken with a data logger (CR1000; Campbell Scientific, Logan, Utah, USA) equipped with a relay multiplexer (AM16/32; Campbell Scientific, Bremen, Germany) and two interfaces.

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

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 depend~~s~~~~eds~~s on the texture of the sample material, its ion concentration, and the temperature. Because of all these factors influencing the sensor readings, the provided values of the WC should be considered as the best possible estimates and not as exact values. For the temperature measurements, thermocouples (Conatex, St. Wendel, Germany) with a tip length of 80 mm and a measurement accuracy of ± 0.5 °C were used. For the light sensors, GaAsP-photodiodes (G1118, Hamamatsu Photonics Deutschland GmbH, Herrsching, Germany) were placed in a housing covered by a convex translucent polytetrafluoroethylene (PTFE) cap and calibrated against a PAR (photosynthetically active radiation) quantum sensor (SKP215; Skye Instruments, Llandrindod Wells, Powys, UK).

The average daily PAR values were calculated from the data collected during daytime, i.e., 6:00 to 18:00, while 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. S~~4~~5). The smoothened data were used for detailed illustrations of seasonal variability (Fig. 2 and S~~5~~6), whereas the 5-minute data were used for calculations in order to also consider short light fleck events. During measurements, the light sensors were regularly checked for algal growth and cleaned accordingly.

2.3 Calculation of the water content (WC)

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

$$EC_{25} = f_T * EC_t, \tag{1}$$

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

$$f_T = 0.447 + 1.4034\ e^{-T/26.815}. \tag{2}$$

The WC sensor ~~was designed~~ has a fixed distance between the sensor pins, which ensures that in all sensors the resistance is equal. This guarantees~~in the manner~~ that the electric voltage, being the inverse resistance, 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).

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 conditions. The dry weight (DW) was determined after drying at 60° C until weight consistency was reached (Caesar et al., 2018). The WC of the sample was calculated according to the formula in Weber et al. (2016):

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

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

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

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

As we got the impression that electrical conductivity values may contain some outliers in the upper data range, we reduced the electrical conductivity data by the uppermost and lowermost 0.1% of the data points (Tab. S3, Fig. S7). ~~The data points of electrical conductivity measured above the upper percentile might be assumed as outliers, due to the rather steep increase to the majority of the values. For an equal correction of the data range also the 0.1 % percentiles have been considered. ~~Accordingly, the water content (WC) was calculated as follows:

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

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

~~8~~The measured electrical conductivity values showed short-time oscillations, which could be removed with a 30-minute smoothing algorithm (Fig. S45). Thus, for all calculations the 30-minute averages ~~have been~~were 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)~~)~~ were combined to obtain average values for each height.

2.4 Meteorology

For the purpose of long-term monitoring, a set of meteorological parameters is being measured within the ATTO project since 2012. In our study we used rainfall data ~~collected ~~measured at 81 m [mm min^{-1}] (Rain gauge TB4, Hydrological Services Pty. Ltd., Australia), relative humidity (RH) measured at 26 m [%], air temperature measured at 26 m [°C] (Termohygrometer CS215, Rotronic Measurement Solutions,UK), and photosynthetically active radiation (PAR) ~~data assessed ~~measured 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 (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. Rainfall ~~is ~~data are presented as accumulated values in millimeters per month, season, or year, which were~~as~~ calculated by an integration of 5-minute intervals. As there were gaps in the data record of the ~~readings of the rain gauge~~rain detection, additional information~~s~~ from the WC sensors ~~was ~~were used to calculate the number of days with rain events. The sensors at 1.5 m height were found to react reliably to rain events. Thus, the gaps in the rain ~~gauge readings~~detection were corrected with the information received from these sensors. Furthermore, the amount of rain within each month was corrected by assuming that during the missing days there were the same amounts as during the rest of the month. Overall, a malfunction of the rain detection was observed on only 6 % of the days (Table S~~2~~4).

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.

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

2.5 Potential physiological activity of bryophytes

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

To assess the potential physiological activity of bryophyte communities, the water and light conditions as major drivers of the metabolism were investigated in somewhat greater detail. The lower water compensation point (WCP) presents the minimum WC that allows positive net photosynthesis. For the tropical ~~species ~~liverwort *Symbiezidium* spp., occurring in the lowlands near sea level in Panama, WCP values in the range between ~ 30 and ~ 80 % have been determined (Wagner et al., 2013) (Table S5~~3~~).

The lower light compensation point (LCP$_l$) represents the minimum light intensity that allows a positive primary production; it ranges between ~ 3 and ~ 12 µmol m^{-2} s^{-1} for bryophytes (based on measurements of *Ectropothecium* cf. *perrotii, Frullania* spec, *Neckera* spec., *Plagiochila divergens, Plagiochila squamulosa, Porothamnium stipiatum, Porotrichum molliculum, Racopilum tomentosum, Radula boryana, Rhizogonium spiniforme*) occurring in African tropical lowland rain forests (Lösch et al., 1994). The epiphytic bryophytes grew in an upper lowland rain forest in the Kahuzi-Biega National Park (Zaire) at about 800 m a. s. l.. Microclimatic conditions inside the forest were similar to the conditions at the ATTO site, as RH ranged around 60-70 % during sunny days and temperatures remained above 20 °C during night and day. At light intensities below the ~~compensation point~~ LCP$_l$ and WCs ~~above~~ below the WCP, respiration rates are higher than NP rates, causing overall net respiration to occur. With regard to temperature, a range for optimum NP (T$_{opt}$~~; 95 % of maximum NP rate reached~~) and an upper compensation point, where NP equals DR~~,~~ (TCP)~~,~~ can be defined. For tropical bryophytes (i. e., the species *Octoblepharum pulvinatum, Orthostichopsis tetragona, Plagiochila* sp. 1, *Stictolejeunea squamata, Symbiezidium* spp., *Zelometeorium patulum*), T$_{opt}$ ranges between 24 and 27 °C and the TCP ranges between 30 and 36 °C, as described by Wagner and coauthors (Wagner et al., 2013). For long-term survival and growth, the bryophytes need to be predominantly exposed to temperatures below the upper compensation point, at least under humid conditions. ~~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).~~ The measurements performed by Wagner et al. (2013) were conducted at a study site (BT) in a lowland rainforest in Western Panama on the Bocas del Toro archipelago, located approximately at sea level. The mean temperature was 25 °C (26 °C during day, 24 °C during night), thus slightly warmer than the temperatures measured at ATTO. With 3,300 mm a^{-1} of rain, BT is in a similar range as the ATTO site (2,540 mm a^{-1}). Unfortunately, literature data on the compensation points are rare, facilitating only a first approximate assessment of the physiological processes (Lösch et al., 1994; Wagner et al., 2013).

A WC above the compensation point allows NP if both light intensity and temperature are above the lower compensation point. If WCs are above the compensation point but light intensities are too low, or if temperatures are above the upper compensation point, net DR occurs. There is also a narrow span of low WCs, when samples are activated already but despite sufficient light intensities only net respiration can be measured. As this span of WCs is narrow and respiration rates are low, it has been neglected in the current calculations. The compensation points for the different parameters are also to some extent interrelated, e.g., the water compensation point of lichens has been shown to slightly increase with increasing temperature (Lange, 1980), but this can be neglected in such a first qualitative approach. Finally, also inter- and intraspecific variation of compensation points could not be considered in the current study.

2.6 Data analysis

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

3 Results

3.1 Microclimatic conditions

3.1.1 Annual fluctuation of monthly mean values

Over the course of the two years of measurements, the monthly mean values of the WC, temperature, and light conditions experienced by the epiphytic bryophyte communities, as well as the above-canopy meteorological conditions, varied between seasons and years. Comparing the two consecutive years, the effect of an El Niño event was clearly detectable, as rainfall amounts were 35 % lower (525 mm versus 805 mm) and relative air humidity 11 % lower (81 % versus 92 %) between October 2015 and February 2016 as compared to the same time-span in the previous year (Fig. 1, Table S~~2~~4).

The monthly mean values of above-canopy PAR (PAR$_{avg}$) were rather stable throughout the years and did not differ between the years 2015 and 2016, ranging between 635~~315~~ and ~~570~~1150 μmol m^{-2} s^{-1} during the daytime (Fig. 1, Table 1a). ~~Within the canopy, t~~The PAR$_{avg}$ values in the understory at 1.5 m also showed only minor seasonal variation, whereas those at higher levels revealed larger variations (~~Table S4~~Fig. 2, Fig. S6)~~. 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$_{avg}$ tended to be higher at 1.5, 8, and 18 m, but lower at 23 m in 2015 compared to 2016.~~ However, the light conditions observed at one individual tree are strongly influenced by its canopy structure and foliation and thus could not be considered as data representative for the canopy in general.

Over the course of the years, the monthly mean temperatures at all heights as well as above-canopy temperatures showed a parallel behavior (Fig. 1). The temperatures decreased in a stepwise manner from the canopy to the understory, and temperatures within bryophytes at 23 m height were frequently higher than the temperatures measured above the canopy (Fig. 1, Table 1a, Fig. S~~6~~8). 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 above-canopy values (Tab. S2, Tab. S4).~~

Over the course of the years, t~~T~~he monthly WCs of epiphytic bryophytes showed similar patterns corresponding to the increasing and decreasing values of rain and~~,~~ RH~~, and WCs 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 S~~2~~4). Monthly rain amounts varied from 9 mm during the dry to 341 mm during the wet season. In 2016, the rain increased from January to March and decreased from March to August, while in 2015 the monthly rain amounts were more variable but still lower throughout the year. The lowest monthly average of the RH was ~~detected ~~observed during the dry season 2015 with 74 ± 15 %. The WC values of epiphytic bryophyte communities were the highest at 23 m, followed by those at 18 m. During the dry seasons, the WCs of mosses at 1.5 m and liverworts at 8 m tended to be the lowest, whereas during the wet seasons ~~only they were rather similar to the WCs of mosses at 8 m, whereas those of ~~the liverworts at 8 m height had the lowest values (Fig. 1, Tab. 2). For most of the height zones t~~T~~he highest monthly averages of the WC values were reached from January to May 2015 and from February to April 2016, whereas the lowest contents were measured from September 2015 to January 2016. The mosses at 8 m height showed rather high WCs during dry season 2015, and these samples showed only a slight alternation between the seasons. Furthermore, the liverworts at 8, 18, and 23 m height showed particularly high ~~WC ~~conductivity values in November and December 2016, which might be caused by a previously required reinstallation. Consequently, the calculated WC values of the reinstalled sensors need to be considered with special care, as they cannot be directly compared to the values prior to reinstallation.

3.1.2 Seasonal changes between wet and dry season

The wet seasons were characterized by a high frequency of precipitation events, large amounts of rain per event, the frequent appearance of fog, and high RH values, ranging mostly above 70 %. In contrast, during the dry season the precipitation events were much rarer and smaller, there was hardly any occurrence of fog, and the RH regularly ~~reached ~~had values below 60 % (Fig. 2, Fig. 3, Fig. S6~~5~~). Comparing environmental conditions of the seasons, the diel amplitudes of ambient light, temperature, and RH were larger in the dry compared to the wet season. While the microclimatic temperature and light conditions within and on top of the epiphytic bryophyte communities followed the above-canopy conditions, modified by canopy shading, the WC of bryophytes did not present a clear pattern (Fig. 3).~~ The temperature and light conditions within and on top of the epiphytic bryophyte communities followed the above-canopy climatic conditions, modified by canopy shading.~~

The above-canopy light intensity (PAR$_{avg}$ daytime) tended to be higher and to show stronger fluctuations in the dry season ~~as compared to~~than in the wet season (970 ± 650 µmol m^{-2} s^{-1} vs. 740 ± 570 µmol m^{-2} s^{-1}) ~~and the values showed stronger fluctuations ~~(Table 2). During both main seasons the average light intensity (PAR$_{avg}$ daytime) decreased from the canopy towards the understory. During the dry season this happened in a regular stepwise manner, whereas in the wet season there were some irregularities, ~~with values at 23 m being lower than at 8 m or 18 m height~~probably caused by the local canopy structure (Fig. 2, 3 Table 2).

~~The temperatures showed larger diel amplitudes in the dry compared to the wet season. ~~The temperatures ~~reflected~~ showed a decreasing gradient from the canopy (wet season: 25.3 ± 2.0 °C, dry season: 27.2± 3.5 °C) towards the understory (wet season: 24.9 ± 1.0 °C, dry season: 25.5± 1.7 °C) and the differences among heights and diel amplitudes were more pronounced during the dry season (Fig. 2, 3, Table 2). 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 (Table~~. S~~2).

~~During 2015 and 2016, rRain occurred in~~During the wet seasons of 2015 and 2016, rain occurred on average on ~~81 and 87~~84 % of the days and in the dry season on ~~25 and 31~~28 % of the days~~, respectively~~. During the wet season, an average RH of 95 ± 9 % and frequently even full saturation was reached, while during the dry season the RH reached ~~on~~ an average value of 87 ± 14 % ~~, while in the wet season the average RH was 95 ± 9 % and frequently even full saturation was reached~~(Table 2). Fog was recorded on ~~56 and 67~~60 % of the days during the wet seasons ~~of 2015 and 2016~~ and on ~~27 and 16~~20 % of the days during the dry seasons, respectively (Fig. 2~~, Table 2~~). According to our observations, fog observed above the canopy normally also occurred (at least to some extent) within the forest.

The WC of the mosses at 1.5 and 8 m and the liverworts at 18 m height responded consistently to rain events, while for the liverworts at 8 and 23 m height not in all cases an immediate response was observed. During the wet season, the mosses at 1.5 m height indicated an increased WC over several days after a rain event, while in the dry season they had lower WC values. Overall, ~~T~~the ~~bryophytes~~ liverworts ~~at the upper three heights~~ showed a regular and pronounced nightly increase of the WC, especially during the dry season (Fig. 2, Fig. S~~5~~6). The WC of the liverworts at 18 m showed a large variation during the dry season in 2016, which was most probably caused by the repositioning in November 2016. N~~Furthermore, n~~ightly fog might serve as an additional source of water, as in some cases the WC of the bryophyte communities increased upon fog events (Fig. S~~7~~9).

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

~~Comparing environmental conditions of 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 not present a clear pattern (Fig. 3). The liverworts in the canopy tended to follow a higher variation 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 diel cycles of WC, temperature, and light conditions experienced by epiphytic bryophyte communities showed varying higher values and amplitudescharacteristics during the wet and the dry seasons compared to the wet season and temperature and WC increasing values from the understory towards the canopy. However, the light conditions at the different heights levels did not show a clear increase from the understory to the canopy, which is most probably an effect of the canopy structure (Fig. 3). The diel variability of light, and temperature, and WC was larger in the canopy than in the understory, while for WC of bryophytes the diel variability was the largest at the 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 not present a clear pattern. The liverworts in the canopy tended to follow a higher amplitude variation 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. For bryophyte communities at the other height levels the amplitudes during the different seasons were less clear.~~

~~The average daily above-canopy light intensities (PAR$_{avg}$) were higher 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 above-canopy climate and the microclimatic sensors, as these mostly were also higher during the dry seasons. Exceptions from that were the lower 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 S56, S67, S87).~~

~~The 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 maximum 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 liverworts was the highest at 23 m and also daily maxima, minima, and amplitudes were the highest at this level. 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 level the amplitude 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.~~

3.2 Potential physiological activity of bryophytes

~~While the availability of water determines the overall time of physiological activity, light is essential for net photosynthesis to occur. Furthermore, high nighttime temperatures cause increased carbon losses due to increased respiration rates.~~

Whereas overall light intensities at the upper three height levels were rather similar, with values ~~mostly ranging between 0 and 100~~below 108, 138, and 147 µmol m^{-2} s^{-1} (at 8, 18, and 23 m height) in 90 % of the time, the values at 1.5 m height remained below 10 µmol m^{-2} s^{-1} during the same time fraction. In contrast to that, ~~and~~ maximum light intensities were relatively similar ~~and~~ high, reaching ~~of~~ 1,550 (1.5 m), 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},~~

~~although maximum values of 1,550 μmol m^{-2} s^{-1} were measured~~ (Fig. 4). In the understory (1.5 m), the lower light compensation point (LCP$_l$), ranging between 3 and 12 μmol m^{-2} s^{-1} (Lösch et al., 1994), was ~~only reached~~ exceeded ~~during~~ in ~~2 – 15~~2-19 % of the ~~reported~~ time during the wet season and in 4-16 % of the time during the dry season~~,~~, whereas at the two ~~higher~~uppermost ~~canopy~~ height levels the bryophytes exceeded~~reached~~ these values ~~during~~ in 34-47 % of the time ~~29 – 47 % of the time~~during both seasons (Table 3).

The ~~microclimatic~~ temperatures inside the moss stands ~~at different height levels within the canopy~~ mainly ranged between 23.0 °C and 33.0 °C at different height levels within the canopy (Fig. 4). In tropical lowland regions, the optimum temperatures for bryophytes (T$_{opt}$) range between 24.0 °C and 27.0 °C (Wagner et al., 2013). In our studies, temperatures in the understory remained within this range in 2-77 % of the time ~~this optimum range was matched during 26 – 7751 % of the time~~ during the wet season and in 9-60 % of the time during the dry season. In the canopy, temperatures remained in this range in 4-54 % of the time during the wet and in 6-34 % of the time during the dry season (Table 3). In the understory, t~~T~~he upper temperature compensation point (TCP) of 30.0 °C – 36.0 °C (Wagner et al., 2013), above which respiration exceeds photosynthesis, was ~~surpassed~~ never surpassed during the wet season and only ~~during~~in 0 – ~~11~~3 % of the time during the dry season. Similarly, ~~in the understory and 0 – 17 %~~at ~~in~~ the uppermost ~~three~~ canopy level~~s~~ the upper TCP was surpassed in 0-3 % of the time during the wet and in 3-26 % of the time during the dry season. Overall, the highest temperatures were reached when the bryophytes were relatively dry and most probably inactive (Fig. S~~8~~10).

The WC of bryophytes differed along the vertical profile, with ~~substantially~~ higher values reached in the canopy (18 and 23 m) than in the understory (1.5 and 8 m). The lower water compensation point (WCP), ranging between 30 and 80 % according to the literature (Wagner et al., 2013), was surpassed by the mosses (1.5 and 8 m) ~~wasreached during~~ in 53 - 100~~0 – 88~~ % of the time during the wet ~~by mosses (1.5 and 8 m)~~and in 4-98 % of the time during the dry season. The liverworts at 8 m height exceeded this value~~,~~ ~~during~~ in 18-98~~2 – 33~~ % of the time during the wet and in 5-86 % of the time during the dry season. At the uppermost two height levels, the liverworts showed no difference of this rate for both seasons, surpassing the WCP in 93-100 % of the time ~~by liverworts (8 m) in the understory, and during 2 – 100 % of the time by liverworts in the canopy~~ (~~18 and 23 m;~~ Fig. 4; Table 3).

~~By comparison of the seasons, the mosses in the understory exceeded during the wet season most frequently the WCP, while the liverworts in the canopy did not show a difference between the seasons (Fig. 4, Table 3).~~

4 Discussion

4.1 Microclimatic conditions

In the current study we measured the microclimatic conditions experienced by epiphytic bryophyte communities at different height levels over the course of more than two years. In previous studies, such data have ~~only~~ been assessed only over short time-spans of hours or days (Chazdon and Fetcher, 1984; Lösch et al., 1994; Romero et al., 2006; Wagner et al., 2013; Zotz et al., 1997).

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

Over the course of two years, the monthly averages of above-canopy ~~average monthly~~ light conditions (PAR$_{avg}$) were rather stable (Table S4). ~~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., 2018), and our data also suggest a slight reduction of monthly ambient PAR$_{max}$ during the dry season 2015 (Table S23)~~ Within the canopy, the monthly PAR$_{avg}$ values at 23 m height tended to be higher during the dry seasons, whereas patterns were less clear at 18 and 8 m height and there was hardly any seasonal variation at 1.5 m height. This was most probably an effect of the canopy structure, cushion orientation, and shading. The sensors at 1.5 and 8 m were installed vertically along the trunk, at 18 m height they were placed on the upper side of a slightly sloped branch, and at 23 m they were positioned on the upper side of a horizontal~~vertical~~ branch. As the light sensors at 23 m height were located within the canopy, newly growing leaves may have periodically shaded the organisms, which may explain the lower monthly PAR$_{avg}$ values at this height level compared to the values at the lower levels, where sunbeams could come through the canopy of neighboring trees and open space.

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

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

The microclimatic mean temperature differences measured inside the bryophyte stands between the understory (1.5 m) and the canopy (23 m) were 1.5 °C in the dry and only 0.5 °C in the wet season. Compared to these results, a temperature difference of 4.0 °C was determined during the dry season in a tropical evergreen forest in Thailand, while in the wet season it was below 1.0 °C, thus corresponding quite well to our results (Thompson and Pinker, 1975) (Table 2). ~~The 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 (Fig. 3~~Tab. S6)~~.) This could be caused by the exposure to strong solar radiation and higher wind velocity in the canopy compared to the sheltered understory (Kruijt et al., 2000).

~~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 substantially lower compared to the previous dry season (Fig. 1, Table 1).~~

Rainfall amounts and relative air humidity values differed between the seasons and also between the years, as they were considerably higher between October 2014 and February 2015 as compared to the following year. This was most probably to an El Niño event, which caused air humidity and WC of bryophytes to be substantially lower compared to the previ~~u~~ous dry season (Fig. 1, Table 1). Generally,~~As expected,~~ the moisture conditions, including rain, fog, and RH, differed between seasons, resulting in different ~~response of the~~ WC patterns of bryophytes~~ upon rain, fog, and high RH differed between seasons~~. ~~The~~A higher frequency of rain during the wet season particularly affected ~~especially~~ the moss communities at the lower levels (1.5 and 8 m; Fig. S6a, Table 2). ~~During the wet season,~~At the same time the higher RH and the more frequent occurrence of fog tended to result somewhat higher WC values of the bryophytes during the wet season~~ affectedand the WC of the moss bryophyte communities at 1.5 and 8 m and the liverwort communities at 23 m to stay increased over longer timetended to be higher~~ as compared to the dry season (Fig. 2, Table ~~2~~2)~~), when the RH values showed lower values during the daytime~~. ~~During the wet season, the frequency of rain was higher, and thus affected especially the moss communities at the lower levels (1.5 and 8 m; Fig. S65a, Table 2, Table 3).~~

~~Furthermore~~The data also suggest that~~,~~ the angle of the stem or branch colonized by the investigated bryophytes played a crucial role for rainwater absorption and the subsequent drying process. The bryophytes at 1.5 and 8 m height were oriented vertically, those at 18 m were placed on the upper side of a slightly sloping branch, and those at 23 m were located on the upper side of a nearly horizontally oriented branch. Long-term climate data have shown that the winds during the wet season predominantly originated from north and north-eastern directions, while during the dry season south- and south-easterly winds prevailed (Pöhlker et al., 2019). At 8 m height, the investigated bryophytes were exposed to the west, and thus were only sometimes directly influenced by precipitation. Also at 23 m height the bryophytes did not always show a clear response to precipitation events, although they were oriented horizontally on a branch (Fig. 2, Fig. S~~5~~6). ~~It can be expected that, besides the dominating wind direction~~Here, also the tree foliation and epiphytic vascular plants might have shielded 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 the 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 ~~may~~often cause no complete water saturation of the bryophytes. Consequently, the organisms tend to dry much quicker than after a strong rain event that causes full~~y~~ saturation~~es~~ of the community. Besides the solar radiation, probably also the higher wind velocities accelerated the desiccation of the epiphytic cryptogams in the canopy (Oliver, 1971). During the dry season, t~~T~~he diel above-canopy RH amplitudes were larger and reached lower values~~ during the dry season~~, thus also promoting quicker drying of bryophyte samples.

In a rain forest environment, condensation and stemflow water need to be considered as potential additional sources of water for epiphytic covers as well as for near-stem vegetation at the forest floor (Lakatos et al., 2012; van Stan and Gordon, 2018). It has been estimated that in tropical forests the stemflow water could provide up to 4 % of the annual rainfall amount (Lloyd and Marques F, 1988; Marin et al., 2000; van Stan and Gordon, 2018), corresponding to maximum values of 68 and 75 mm in the years 2015 and 2016 at the ATTO site. The WC of bryophytes in the understory responded clearly to rain events ~~showed a high variability~~ during the wet season (Fig. 3a), and subsequently water was lost gradually indicating that large amounts of water were taken up during prolonged rain events, which were subsequently lost again ~~in a stepwise manner~~rather gradually, with bryophytes ~~often~~ staying wet and active over prolonged time spans (Fig. 2, Fig. S~~5~~6). The high WC of the bryophyte samples in the canopy ~~might~~ can be ~~partly~~ explained by the ~~different~~ higher water holding capacity of the liverwort *Symbiezidium*, which dominated in the canopy, and by its growth on inclined or vertical stems, where water drainage is less effective as compared to the vertical stem at the lower two levels. The relevance of the water holding capacity for the water content of different bryophyte species has already been described in several other studies (Lakatos et al., 2006; Romero et al., 2006; Williams and Flanagan, 1996). ~~The species dominating the measurements in the canopy (23, 18, and 8 m) was a liverwort in the understory (1.5 and 8 m) moss species were dominating the measurements.~~

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

4.2 Potential physiological activity of bryophytes

The microenvironmental conditions influence the WC of epiphytic bryophyte communities, but the ability to deal with these conditions differs among species (interspecific variability), being determined by morphological and physiological features. Apart from the interspecific variability,~~long-term adaptation of the metabolic properties,~~ the performance of a single species under differing microenvironmental conditions can also be modulated by short-term acclimation and long-term adaption processes~~ (intraspecific variability)~~, with the latter being driven by environmental exposure, genetic variation among populations, and plasticity, as, e.g., shown for bryophytes and lichens (Cornelissen et al., 2007; Marks et al., 2019; Pardow et al., 2010). These ~~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 on the basis of climatic conditions alone (Raggio et al., 2017).~~ During our study, we measured the microenvironmental~~ecological~~ conditions of epiphytic bryophytes and~~also~~ observed bryophyte taxa to vary depending on these~~ microenvironmental conditions~~. Additionally, we estimated the potential ranges of physiological activity based on the compensation points for light, temperature, and WC, which have been reported from other studies in tropical forests (Lösch et al., 1994; Wagner et al., 2013). Whereas at the stem bases close to the ground the moss species *Sematophyllum subsimplex*, *Octoblepharum cocuiense,* and *Leucobryum martianum* were dominating, the liverwort *Symbiezidium barbiflorum* was the main species occurring at higher levels along the tree stem. These species have also been reported as being frequent at other tropical rain forest sites (Campos et al., 2015; Dislich et al., 2018; Gradstein and Salazar Allen, 1992; Mota de Oliveira et al., 2009; Pinheiro da Costa, 1999).

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

The temperature regulates the overall velocity of metabolic processes~~, ~~.~~hence~~ While it has a strong impact on the respiration, ~~while ~~the photosynthetic light reaction is by far less ~~sensitive ~~affected by it (Elbert et al., 2012; Green and Proctor, 2016; Lange et al., 1998). As the measured net photosynthesis rates are the sum of simultaneously occurring photosynthesis and respiration processes, positive net photosynthesis may still be reached at higher temperatures, if the photosynthetic capacity is high enough, whereas during the night, high temperatures could cause a major loss of carbon due to high respiration rates (Lange et al., 2000). In the course of our study, the lowest temperatures predominantly occurred during the night, contributing to lower respiration rates, and values were mostly below the upper TCP. Thus, the temperature did not seem to be a limiting factor for the physiological activity of epiphytic bryophytes in this environment (Fig. S~~8~~10). Similarly, Wagner and coauthors (Wagner et al., 2013) stated that the temperature likely was not a limiting factor for ~~NP and growth~~the overall carbon balance of the bryophytes investigated ~~by them ~~in a low~~-land~~ and highland rainforest in Panama. Unexpectedly, t~~T~~he WC of bryophytes has been shown to be higher in the canopy than in the understory. In the understory, the WCP was ~~reached ~~surpassed ~~between ~~in 4~~1 and -~~54~~36~~ % of the time during the dry season and in 53-95 % of the time during the wet season~~, depending on the literature value being considered~~, whereas at 18 and 23 -m it was exceeded~~reached during ~~in ~~~3~~93 – 100 -% of the time, without a clear difference between the seasons. In the understory, the WC of cryptogams seemed~~s~~ 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).~~, whereas i~~I~~n the canopy, the samples stayed relatively homogeneously wet over long time spans (Fig. 2). This was unexpected at first sight, as one would expect them to dry quickly at the higher canopy levels. However, as the samples at the two upper canopy levels grew "sitting on top" of nearly horizontal branches~~vertical stems~~, they ~~probably ~~presumably could store the water over longer time spans as compared to the bryophytes at the lower trunk section, which grew on the vertical stem. Additionally, the liverwort community in the canopy seemed to form thicker and denser cushions, which could store water more effectively as compared to the mosses in the understory, which occurred in thin and rather loose cushions (Fig. S4).

It is difficult to distinguish between the effect of fog and high RH, as fog occurs when high RH values persist already. However, some events indicate that the~~ bryophyte~~ WC of bryophytes could increase upon fog (Fig. S~~7~~9), which has also been shown in some other studies (León-Vargas et al., 2006). Also condensation needs to be considered as a water source for cryptogams, as demonstrated for epiphytic lichens (Lakatos et al., 2012). In their study on corticolous epiphytic lichens in a tropical lowland cloud forest, Lakatos and coauthors showed that lichens benefit from dew formation on the thallus surface during noon, and we can assume ~~that ~~similar processes to occur quite regularly on epiphytic cryptogams (Lakatos et al., 2012). Unfortunately, this factor could not be evaluated in this study, because some relevant parameters for its calculation were not monitored.

~~Based on o~~O~~ur measurements combined with~~ Utilizing the compensation points of water, light, and temperature, one can make rough estimates of the physiological activity patterns ~~time frames, when these points are reached or exceeded can be madeof the potential time of NP and DR for~~ of the bryophytes at the different height levels (Table 3). Whereas the lower end of the WCP range (30 % DW) was ~~reached~~ exceeded during 100 % of the time by the liverworts at the two upper most ~~two~~ height levels, the liverworts at 8 -m exceeded~~reached~~ this value only ~~during~~ in 86~~33~~ % of the time during the dry season and in 98 % of the time during the wet season. ~~, and t~~The mosses at 1.5 m height exceeded this value in 54 % of the time during the dry season and in 95 % of the time during the wet season. ~~If~~Considering a WCP of 80 %~~will be considered~~, the mosses in the understory only exceed this value in 4 % and in 53 % of the time during the dry and the wet season, respectively. Thus, for mosses in the understory, the level of the WCP is highly relevant, whereas for the liverworts in the canopy the complete range of values allows long durations of physiological activity. ~~and 8 m height reached it only during 36 and 88 % of the time, respectively.~~ For the LCP_l (ranging between 3 and 12 µmol m^{-2} s^{-1}) an even more critical pattern was observed, as the ~~data suggest that by~~ communities at the ground level surpassed it~~, it was reached~~ only ~~during~~ in ~~2~~4-16 % and in 2-19 % of the time during the dry and the wet season, respectively. In contrast to this,~~W by communities at the ground level, whereas~~ bryophytes~~those~~ at the higher levels (18, 23 m) surpassed these CPs~~it~~ ~~during~~in ~~∼30 – 40~~38-47 % and in 34-46 % of the time during the dry and the wet season, respectively. ~~In contrast~~Contrastingly, ~~to these factors,~~ the temperature ~~was~~ only rarely was limiting NP and there were no major differences between the height levels or the seasons. At all height levels T_{opt} was reached in 5-60 % of the time during the dry season and in 2-77 % of the time during the wet season.

Combining the ranges of compensation points allows, ~~of the environmental factors needed~~ a rough estimation of~~for~~ the time fractions when NP and DR occur. Our data suggest~~ed~~ that ~~NP and DR~~ at the upper two height levels NP occurred ~~during~~ in ~~∼30 – 60~~27-43 % ~~(NP)~~ and DR in ~~∼30 – 50~~56-66 % ~~(DR)~~ of the time during the wet season and in 21-43 % (NP) and in 51-59 % (DR) of the time during the dry season, respectively~~, thus being in a reasonable range~~. At the understory~~lower levels~~, however, the durations of ~~NP and DR~~physiological activity w~~ere~~as relatively short and the results for the ~~ground l~~lowest level suggested that NP and DR occurred only ~~during~~ in ~~∼5~~1-15 % (NP) and in 53-79 % (DR) of the time during the wet season and ~~during~~in ~~∼10 – 25~~ 0-10 % (NP) and in 16-52 % (DR) of the time during the dry season. The large discrepancy between the time ranges for NP and DR calculated for the bryophytes in the canopy and the understory~~,~~ ~~These results appear highly unrealistic and thus we~~ gives reason to expect the LCP_l and the WCP to be at the lower ~~levels~~ end of the range (3 µmol m^{-2} s^{-1}, 30 %) for the bryophytes at the lowest height level and to be at the upper end of the range (12 µmol m^{-2} s^{-1}, 80 %) for the bryophytes at the two uppermost height levels. ~~and particularly at the ground level to be lower values than the values that have been published up to now for tropical bryophytes.~~ For other habitats, LCP_ls~~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. However, one also has to keep in mind that the uncertainty inherent in the microclimatic data directly impacts the calculated physiological patterns.

In the environment being studied, the acclimation~~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~~and also within one division the interspecific variability can also be large.

5 Conclusions

The microclimatic conditions experienced by bryophytes are being assessed in long-term measurements at the ATTO site since October 2014. These measurements provide a unique data set of the micrometeorological conditions within the understory and the inner canopy of tropical rain forests and facilitate a rough estimation of the physiological activity patterns of epiphytic bryophytes along a vertical gradient. Within this tropical rain forest habitat, the WC has turned out to be the key parameter controlling the overall physiological activity of the organisms with major differences between organisms of the canopy and the understory. In the understory the WC of the bryophytes~~ WC is~~ was mostly relatively low~~,~~ and only~~but~~ stayed~~s~~ high for a ~~longer time~~few days after an intense rain~~s~~ event. In contrast to that, the ~~water content~~WC of the bryophytes at higher levels remains high ~~and at similar values~~ over most of the time, probably caused by the bryophyte~~s~~ morphology and also their growth habitat on top of inclined or ~~a vertical stem~~horizontal branches. In the canopy, the dominating liverworts responded to the nightly increase of the RH, which was not observed for the mosses in the understory. Thus, the relevant water source for bryophytes in the understory might be rain, while for the bryophytes in the canopy the nightly increase of the RH might be relevant for an activation of the physiological processes. The light intensity during periods of physiological activity mainly determines whether NP dominates or carbon is lost by dominating respiration. As the temperature shows only minor spatial, diel, and seasonal variation relative to the physiological tolerance of the bryophytes, it ~~might~~ seems to be of minor physiological relevance within the given habitat.

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

Data availability

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

Supplement link

Author contribution

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

Disclaimer

The authors declare that they have no conflict of interest.

Special issue statement

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Tables

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

(a)

Height [m]	2015 Mean	 ± SD	2016 Mean	 ± SD
PAR_{avg} daytime[µmol m^{-2} s^{-1}]				
above-canopy, 75	911	678	841	653
23	34	1	58	8
18	45	15	34	11
8	35	19	17	10
1.5	5	35	4	20
PAR_{max} [µmol m^{-2} s^{-1}]				
above-canopy, 75	2043	579	2153	433
23	320	24	497	51
18	310	38	331	26
8	322	236	116	86
1.5	172	0	99	140
Temperature [°C]				
above-canopy, 26	26.6	3.4	26.4	3.1
23	25.9	1.0	26.5	0.5
18	26.2	0.0	26.3	0.0
8	25.8	0.2	25.8	0.2
1.5	25.4	0.0	25.5	0.1
Water content [%]				
23, Liverwort	282~~27~~	117~~42~~	280~~116~~	438~~44~~
18, Liverwort	181~~107~~	50~~40~~	308~~170~~	309~~172~~
8, Liverwort	52~~25~~	14~~7~~	140~~67~~	288~~119~~
8, Moss	182~~55~~	93~~24~~	167~~57~~	256~~38~~
1.5 Moss	86~~41~~	37~~50~~	69~~31~~	415~~35~~

(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,~~mean photosynthetically active radiation (PAR_{avg}), the daily maximum of photosynthetically active radiation (PAR_{max}), the temperature, and the above-canopy relative humidity (RH) or ~~/~~water content (WC) of bryophytes determined at different height levels and above the canopy. Mean values for the respective seasons were calculated from 5-minute intervals of the years 2015 and 2016, except for PARmax, where the daily maximum values 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	±	Mean	± SD
Wet season								
above-canopy	738	566	2086	515	25.6	2.5	954~~143~~	9~~36~~
23 Liverwort	30	3	248	194	25.3	2.0	283~~125~~	83~~33~~
18 Liverwort	39	12	282	175	25.2	1.9	197~~113~~	66~~37~~
8 Liverwort	31	26	144		24.9	1.1	66~~31~~	22~~10~~
8 Moss							182~~64~~	63~~29~~
1.5 Moss	4	15	114	224	24.9	1.0	121~~60~~	91~~50~~
Transitional season Wet-Dry								
above-canopy	861	649	2227	182	25.8	3.0	91~~143~~	11~~57~~
23 Liverwort	41	72	414	252	25.7	2.8	308~~128~~	109~~41~~
18 Liverwort	44	54	351	123	25.4	2.3	200~~127~~	34~~20~~
8 Liverwort	66	88	165	218	24.9	1.4	53~~25~~	10~~5~~
8 Moss							161~~54~~	56~~21~~
1.5 Moss	2	12	61	102	24.6	1.1	55~~24~~	28~~15~~
Dry season								
above-canopy	973	647	2100	609	26.7	3.4	87~~119~~	14~~52~~
23 Liverwort	55	9	503	231	27.2	3.5	273~~122~~	125~~52~~
18 Liverwort	41	13	412	190	26.5	2.9	188~~107~~	89~~52~~
8 Liverwort	23	16	295	268	26.0	2.1	63~~32~~	45~~28~~
8 Moss							166~~51~~	70~~33~~
1.5 Moss	6	25	209	299	25.5	1.7	53~~23~~	37~~20~~
Transitional season Dry-Wet								
above-canopy	785	617	1988	509	26.5	3.3	85~~141~~	15~~67~~
23 Liverwort	55	91	530	297	27.2	3.7	289~~130~~	113~~48~~
18 Liverwort	37	28	185	109	26.6	3.0	227~~137~~	121~~75~~
8 Liverwort	21	47	269	178	26.3	2.5	112~~61~~	84~~49~~
8 Moss							180~~56~~	67~~24~~
1.5 Moss	4	20	107	113	26.0	2.1	74~~35~~	60~~33~~

Table 3: The potential time ~~ranges~~ fractions [%], during which the epiphytic bryophytes at the different height levels ~~levels bryophytes at the different height levels~~ exceeded ~~reached~~ the lower compensation points of light (LCP_l), ~~the optimal temperature for net photosynthesis (T_{opt}),~~ the upper compensation points for temperature (TCP), ~~and~~ the lower compensation points for water (WCP), and reached the optimal temperature for net photosynthesis (T_{opt}). The results are shown separately for a) the wet season (February–May) and b) the dry season (August–November~~; c~~). ~~The conditions at which the compensation points were reached are listed, and the potential time ranges, during which NP and DR might occur were~~are ~~listed.~~ Values are given for the different height levels (1.5, –8, –18, –23 m) and bryophyte divisions (M=moss, L=liverwort). For the net photosynthesis (NP) it is required that~~:~~ WC > WCP, PAR > LCP_l and T > TCP, for the dark respiration (DR) it is necessary that WC > WCP and PAR < LCP_l or WC > WCP and T > TCP. Five-minute averages of measurements during the entire measurement period from October 2014 to December 2016 were considered. The ranges of the compensation points (CP) and the optimum~~al~~ temperature ~~ranges~~ (opt) were reported in Lösch (1994) and Wagner et al. (2013) (see Table S~~3~~4).

~~Complete project duration~~

~~Height~~ ~~-~~	~~Division~~ ~~L/M~~	~~LCP_l~~ ~~≥3-12~~ ~~µmol m^{-2} s^{-1}~~	~~T_{opt}~~ ~~24.0-27.0~~ ~~° C~~	~~TCP~~ ~~≥30.0-36.0~~ ~~° C~~	~~WCP~~ ~~≥30-80~~ ~~% DW~~	~~Condi- for NP~~ ~~LCP_l/TC~~ ~~-~~	~~NP~~ ~~WC > WCP & PAR > LCP_l & T < TCP~~	~~DR~~ ~~WC > WCP & PAR < LCP_l or WC > WCP & T > TCP~~
~~[m]~~		~~Time fraction when cardinal points are reached/exceeded [% of time]~~				~~µmol m^{-2} s^{-1}/°C/%DW~~	~~Time fraction when cardinal points are reached [% of time]~~	
~~23 L~~	~~L~~	~~43-4536-45~~	~~6-46~~	~~2-16~~	~~99-1002-~~	~~3-12/30-~~	~~28-5831-58~~	~~40-5347~~
~~18 L~~	~~L~~	~~45-4839-47~~	~~6-51~~	~~0-13~~	~~97-1004-~~	~~3-12/30-~~	~~27-5934-64~~	~~31-4130-33~~
~~8 L~~	~~L~~	~~37-4229-40~~	~~13-29~~	~~0-17~~	~~12-962-33~~	~~3-12/30-~~	~~1-234-48~~	~~3-1610-38~~
~~8 M~~	~~M~~	~~-~~			~~91-990-88~~	~~3-12/30-~~	~~5-4625-55~~	~~9-3037-45~~
~~1.5 M~~	~~M~~	~~8-282-15~~	~~14-30~~	~~0-11~~	~~29-851-36~~	~~3-12/30-~~	~~0-126~~	~~10-2624-58~~

a) Wet season

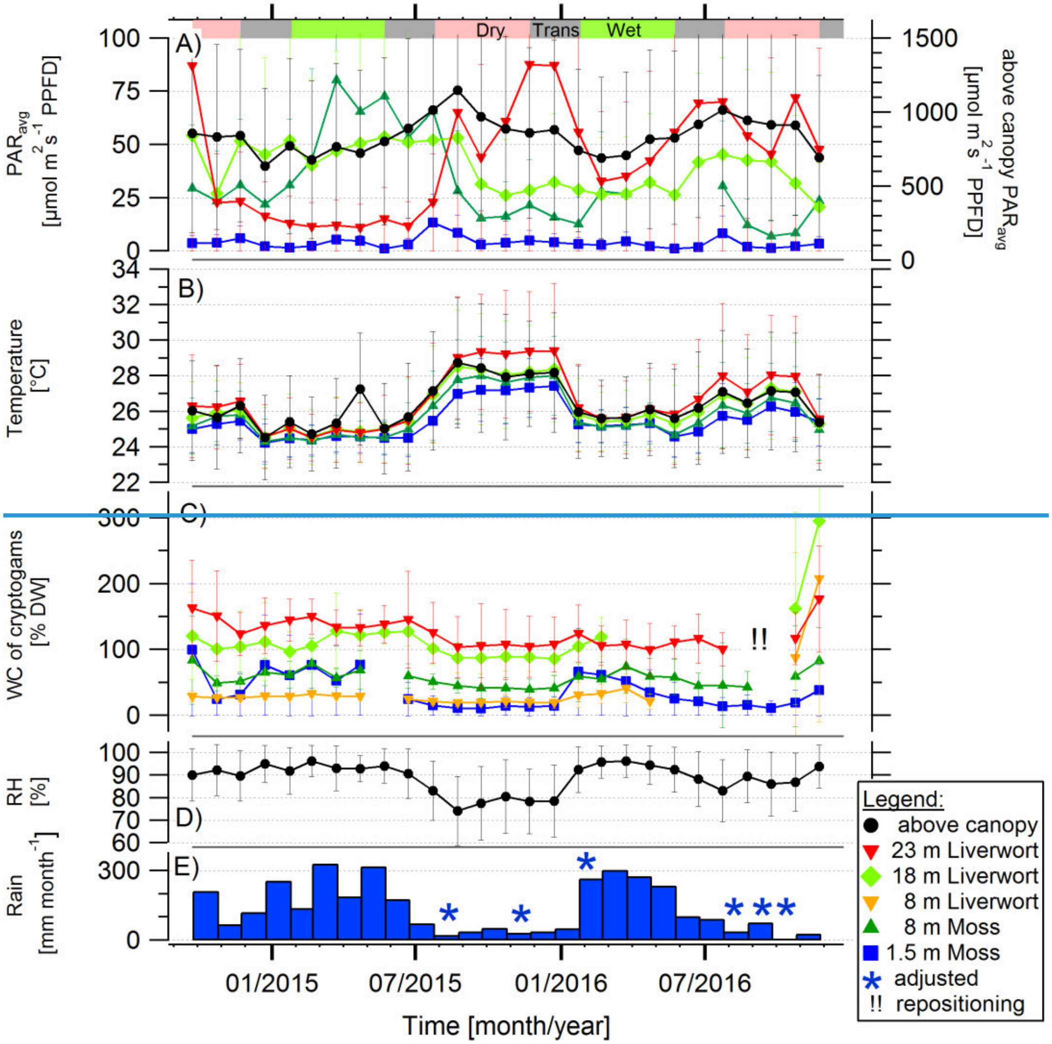
Height	Division	**LCP_l**	**T_{opt}**	**TCP**	**WCP**	NP	DR
		≥ 3-12	24.0-27.0	≥ 30.0-36.0	≥ 30-80		
		µmol m^{-2} s^{-1}	° C	° C	% DW		
[m]	L/M	**Time fraction when cardinal points are reached/exceeded [% of time]**					
23	L	34-43	4-54	0-3	98-100	27-38	62-66
18	L	40-46	4-55	0-2	96-100	32-43	56-57
8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

b) Dry season

Height	Division	**LCP_l**	**T_{opt}**	**TCP**	**WCP**	NP	DR

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

Figures


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

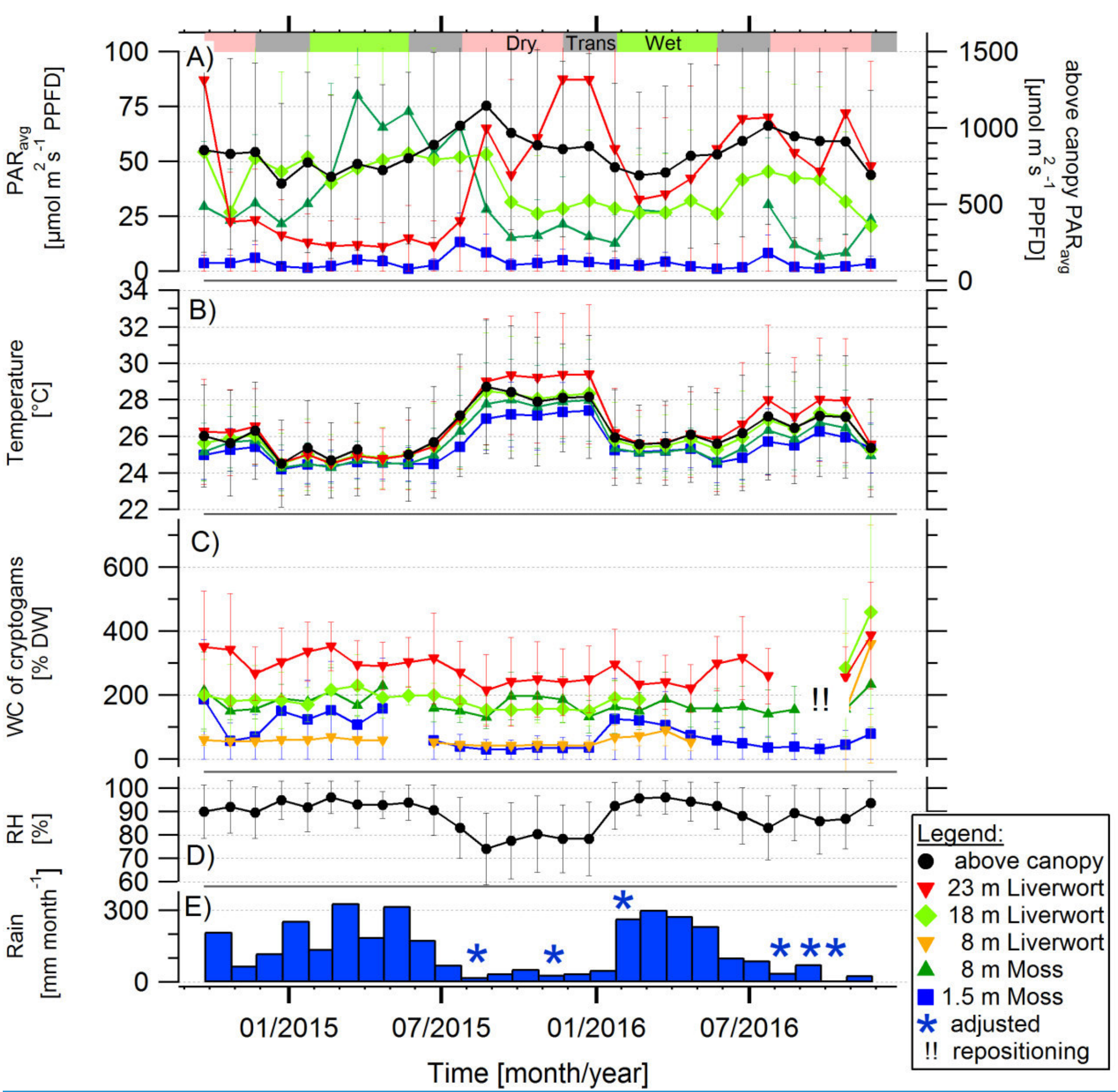
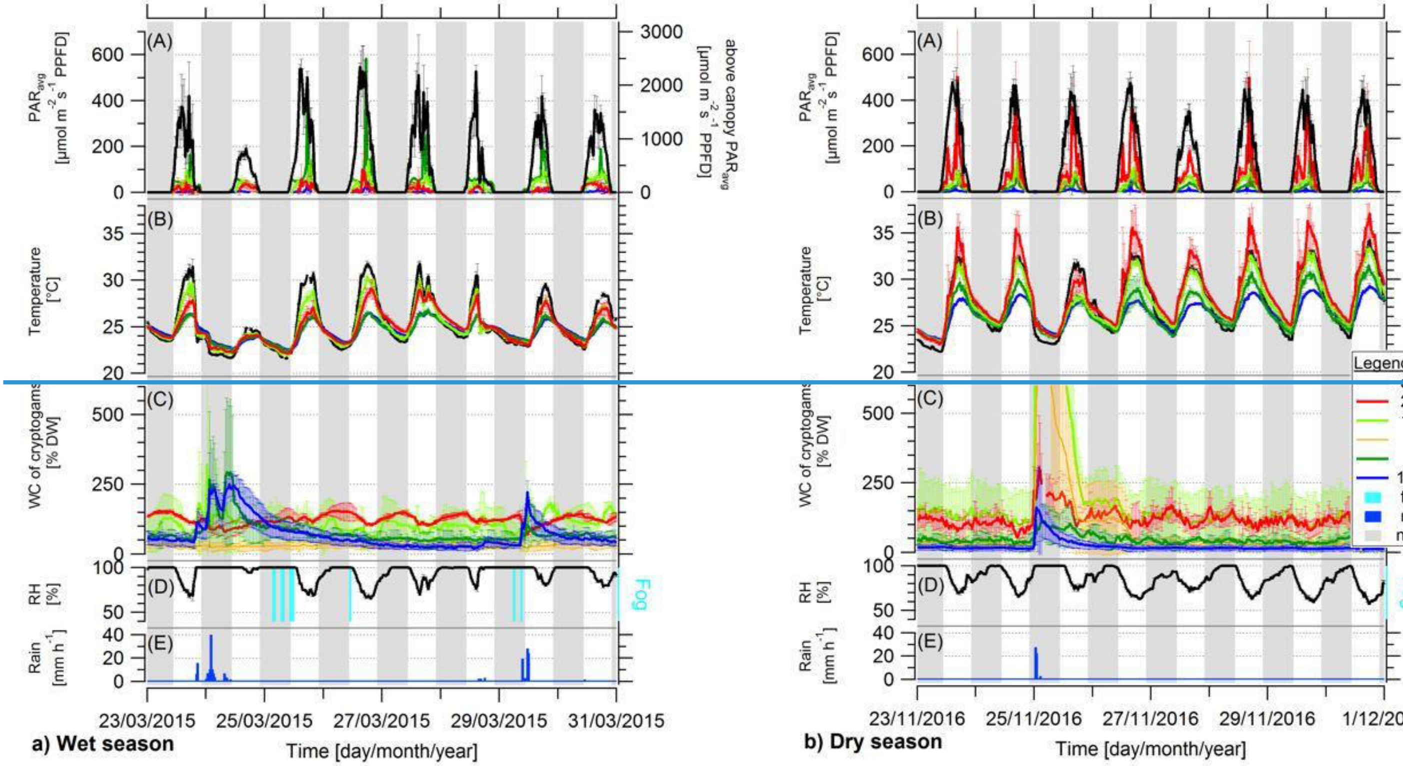


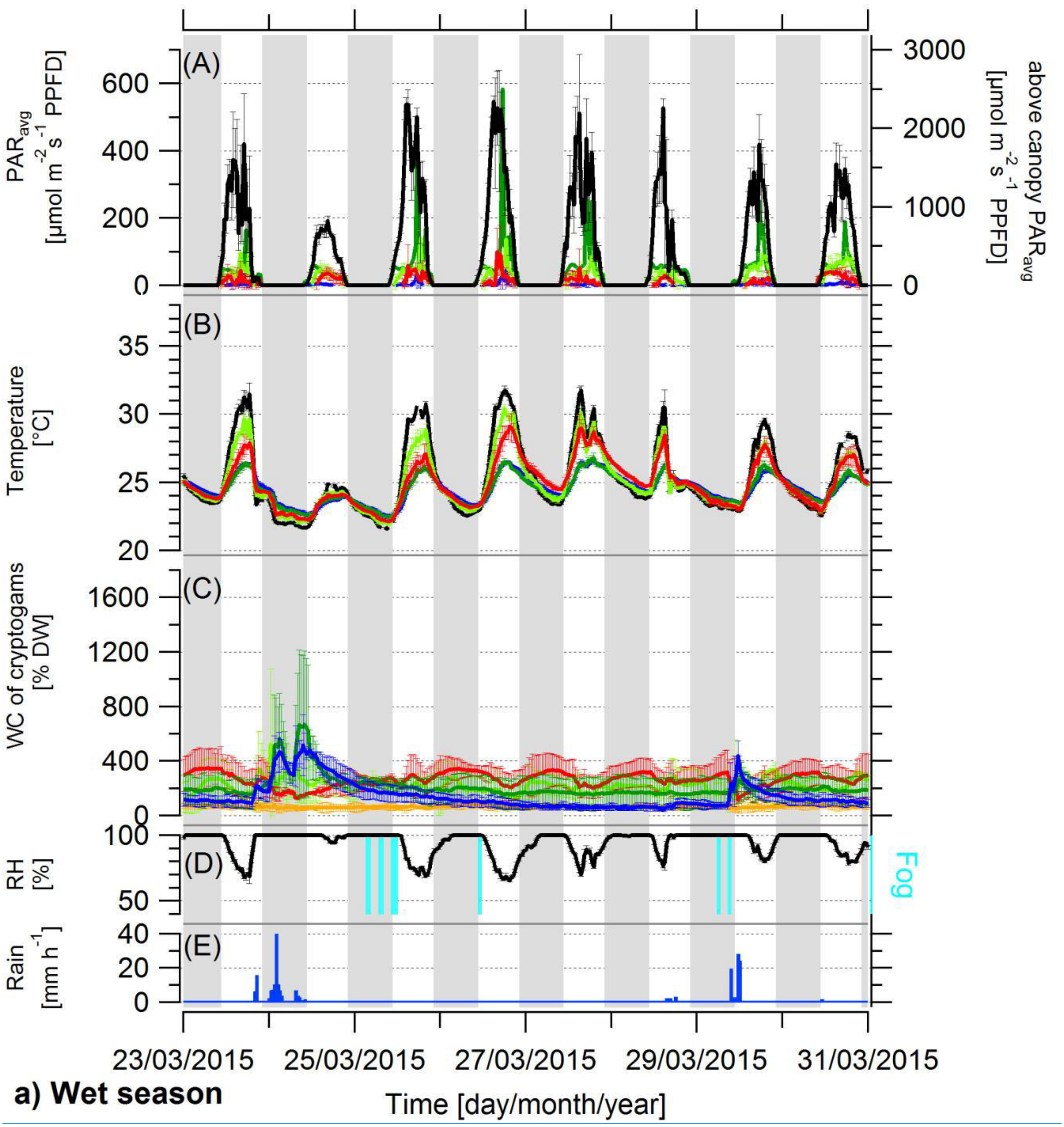
Figure 1: Mean light condition (PAR$_{avg}$), temperatures, and w~~W~~ater content~~,~~ (WC)~~, temperature, and light conditions~~ experienced by bryophyte communities, and above-canopy meteorological conditions in the Amazonian rain forest. The micrometeorological parameters on top/within epiphytic~~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

temperature (at 26 m), (D) monthly mean value of relative air humidity (RH at 26 m height), and (E) monthly amount of rain. Data of replicate sensors installed within communities at the same height level were pooled, while above-canopy parameters were measured with one sensor each. Colored horizontal bars in the upper part of the figure indicate the seasons. Exact values and additional data are presented in Tables S~~2~~4 and S~~4~~6.



a) Wet season

b) Dry season


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

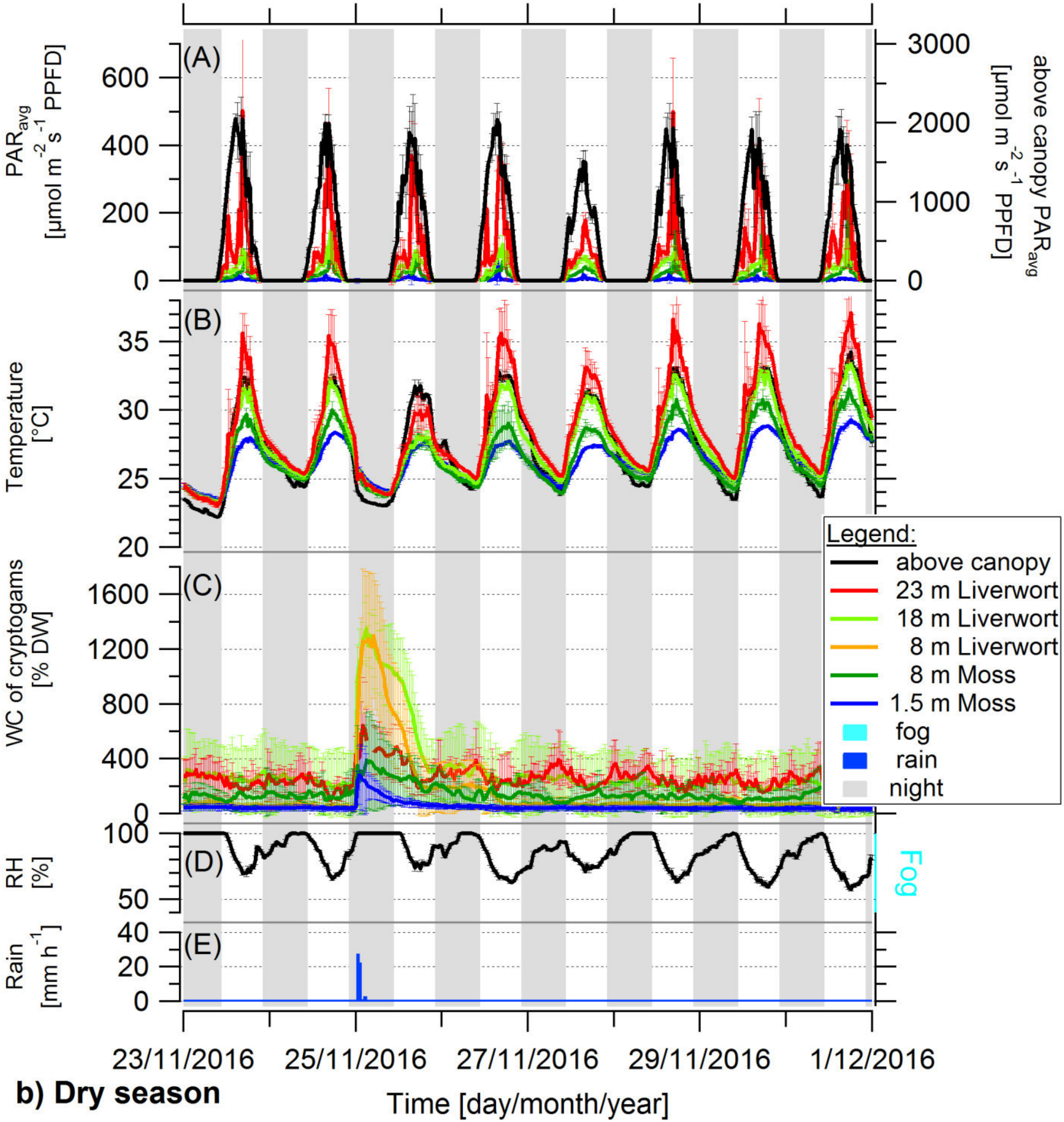
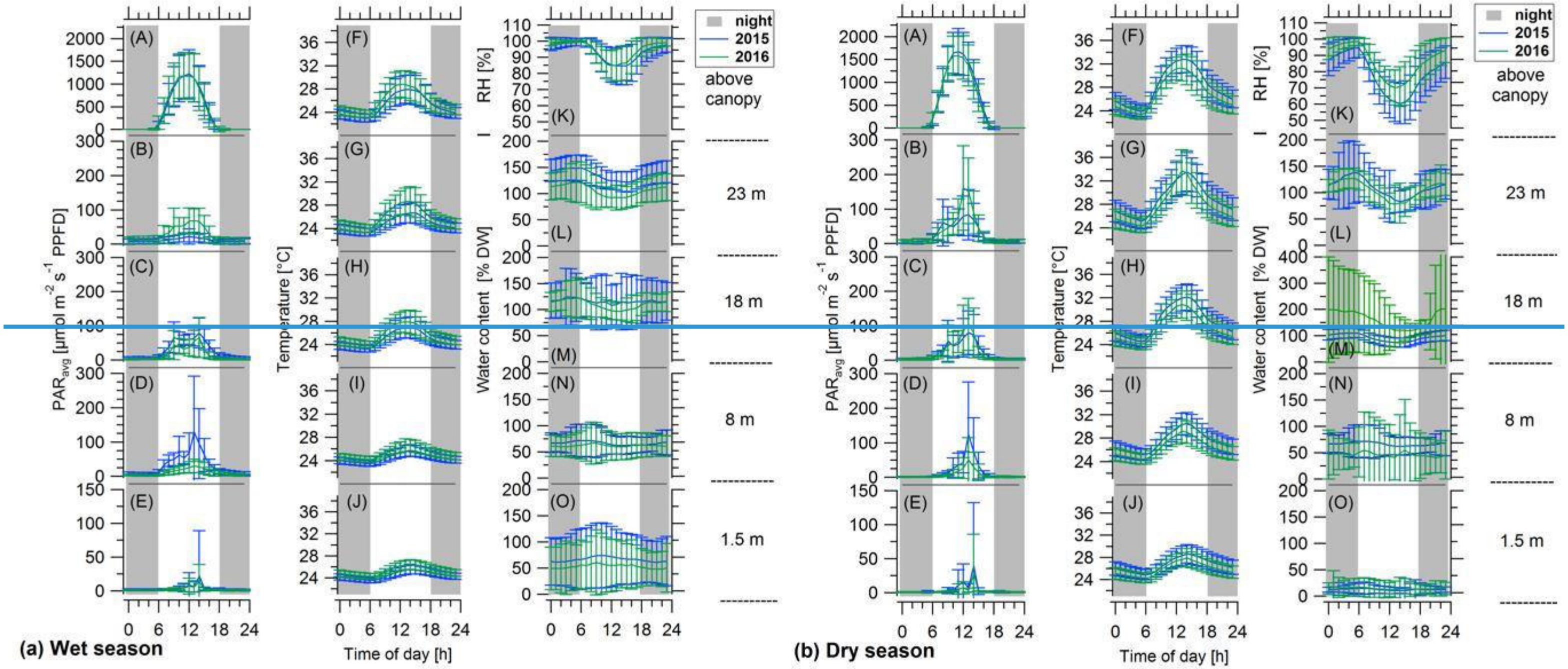


Figure 2: Representative periods during the wet and dry season under average conditions, showing light condition (PAR$_{avg}$), temperature, and water content (WC)~~, temperature, and light condition (PAR$_{avg}$)~~ of bryophytes, and

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


(a) Wet season
(b) Dry season
PARavg [µmol m-2 s-1 PPFD]
Temperature [°C]
RH [%]
Water content [% DW]
Time of day [h]
(A)
(B)
(C)
(D)
(E)
(F)
(G)
(H)
(I)
(J)
(K)
(L)
(M)
(N)
(O)
night
2015
2016
above canopy
23 m
18 m
8 m
1.5 m
0 6 12 18 24

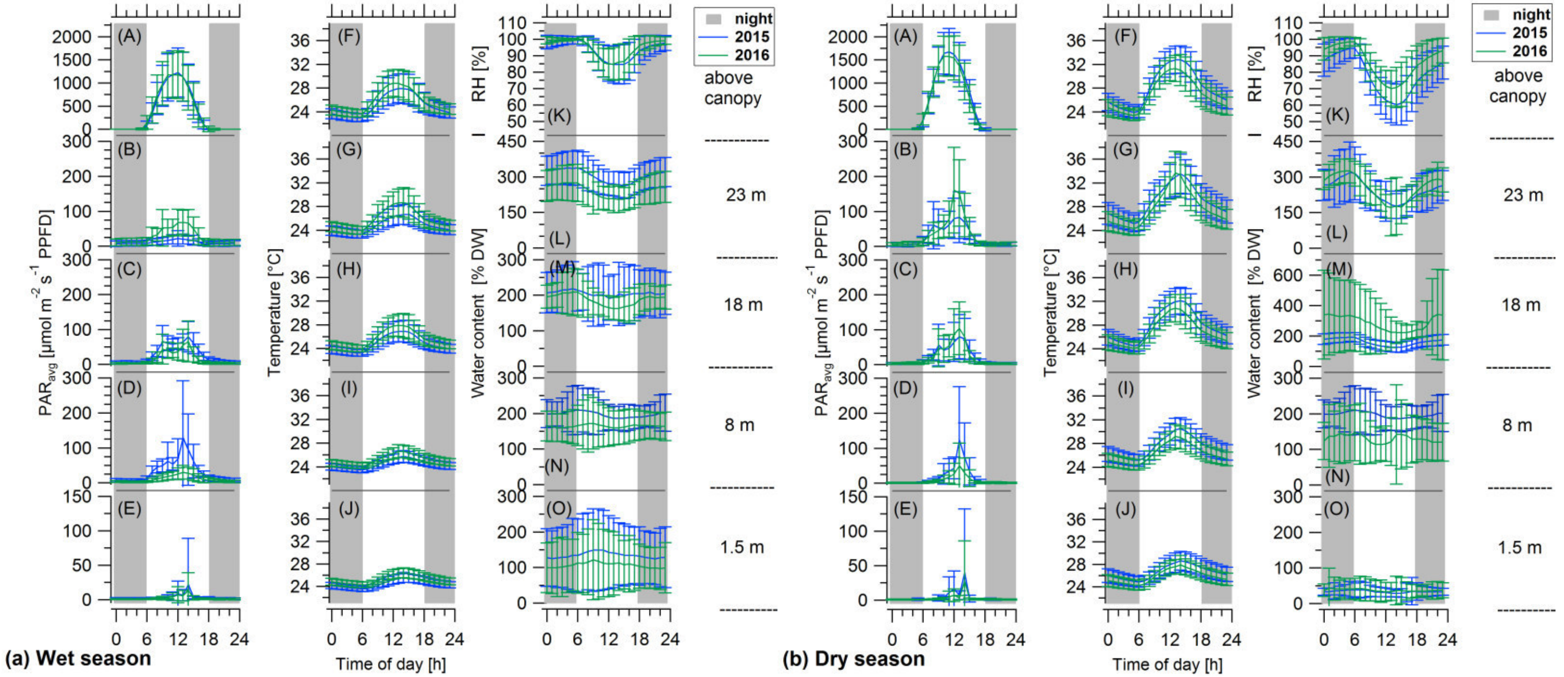
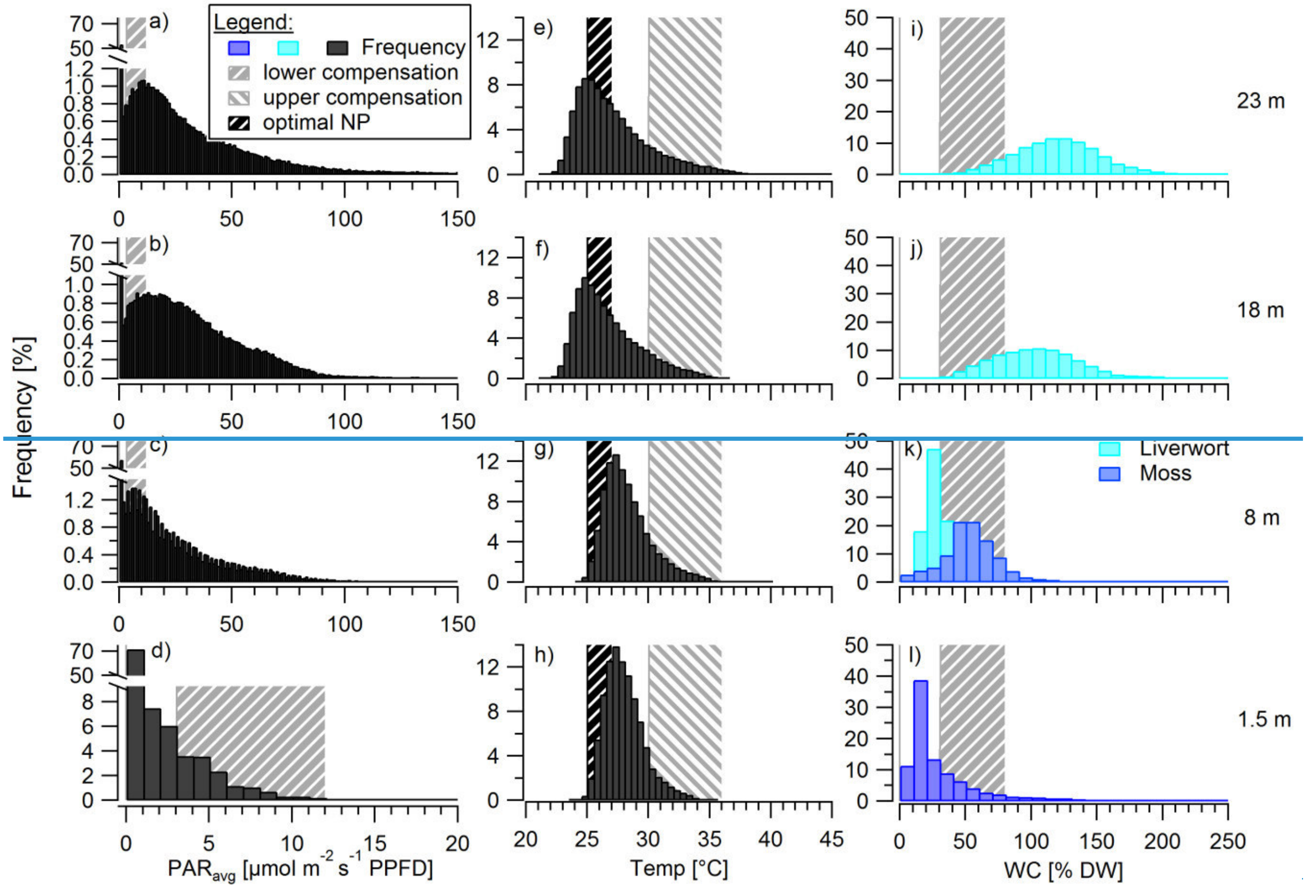
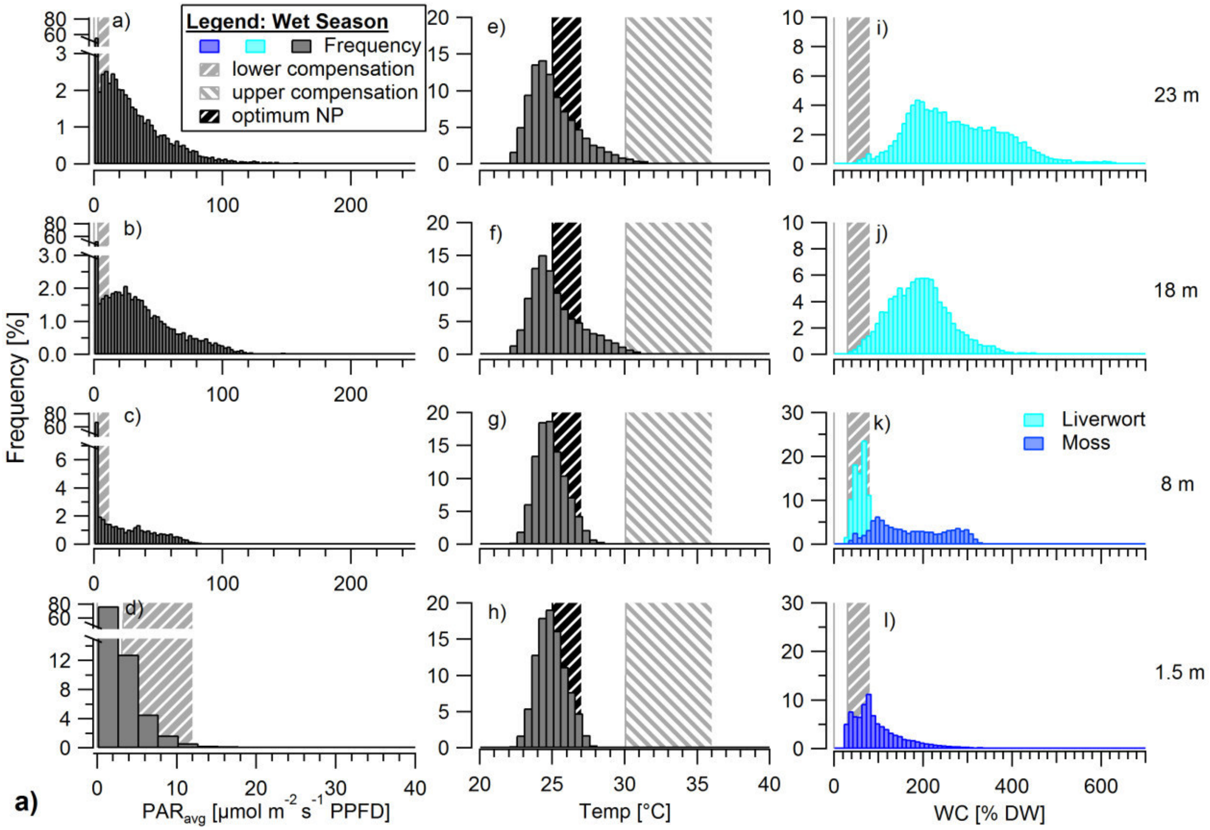


Figure 3: Mean diurnal cycles of light conditions (PAR$_{avg}$), temperature, and water content (WC)~~, temperature, and light conditions~~ of bryophytes, and above-canopy meteorological parameters during (a) wet season and (b) dry season of the years 2015 (blue lines) and 2016 (green lines)~~ based on 30-minute intervals~~. The above-canopy meteorological parameters comprise (A) the ~~above-canopy~~ photosynthetically active radiation (PAR$_{avg}$ at 75 m), (F) the ~~above-canopy~~ temperature (at 26 m), and (K) the relative air humidity (RH at 26 m height). 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 WC of cryptogamic communities at different height levels. Diel cycles were calculated from 30-minute intervals of the whole seasons and show hourly mean values ± SD. Data of the sensors installed at the same height level were pooled, while the above-canopy parameters were measured with one sensor each. For the WC at 8 m height data of the mosses are shown. Nighttime is shaded in grey (06:00 – 18:00 LT). ~~Comparisons of maximum and minimum values and diel amplitudes of light, temperature, and humidity~~ moisture ~~between seasons are shown in Table S5~~6 ~~– S7~~8~~.~~


a)
b)
c)
d)
e)
f)
g)
h)
i)
j)
k)
l)
Legend:
Frequency
lower compensation
upper compensation
optimal NP
Liverwort
Moss
23 m
18 m
8 m
1.5 m
Frequency [%]
0
50
100
150
0
5
10
15
20
PAR$_{avg}$ [µmol m^{-2} s^{-1} PPFD]
0.0
0.2
0.4
0.6
0.8
1.0
1.2
50
70
0
2
4
6
8
20
25
30
35
40
45
Temp [°C]
0
4
8
12
0
50
100
150
200
250
WC [% DW]
0
10
20
30
40
50


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

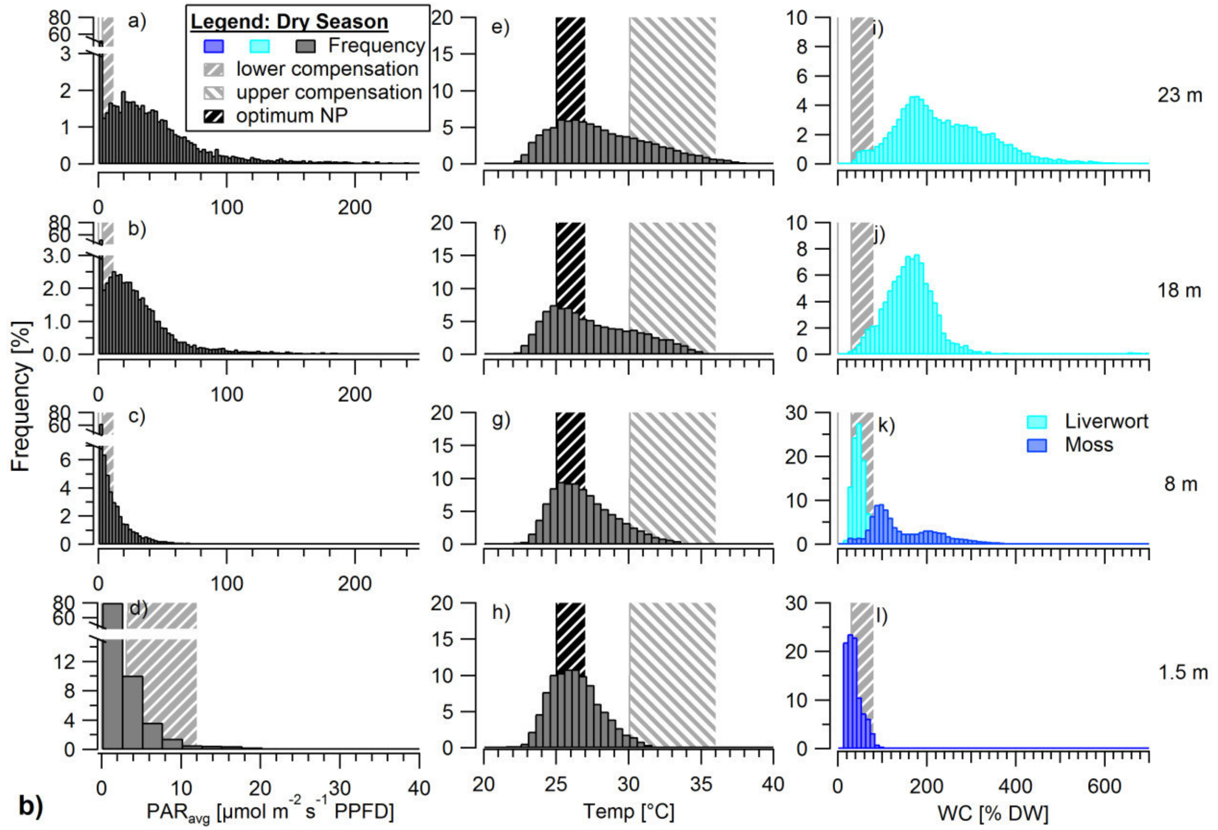


Figure 4: Frequency of mean photosynthetically active radiation (PAR$_{avg}$; a – d), temperature (Temp; e – h), and water content (WC; i – l) measured on top/within bryophytes at 1.5, 8, 18, and 23 m height ~~within the canopy~~ during (a) the wet and (b) the dry season. Calculation of the histograms based on 30-minute intervals. Shaded areas represent the ranges of lower compensation (PAR, WC), upper compensation (temperature), and the optimum (temperature) for ~~optimum~~ net photosynthesis ~~(black shading)~~. Value ranges are adopted from Lösch (1994) and Wagner et al., (2013) (Table S~~3~~5). Bin sizes: PAR: 2.5~~1~~ µmol m^{-2} s^{-1}; temperature: 0.5 °C; WC: 10 %.

Supplement

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

Contents:

Figures S1 – S10~~8~~

Tables S1 – S6~~7~~

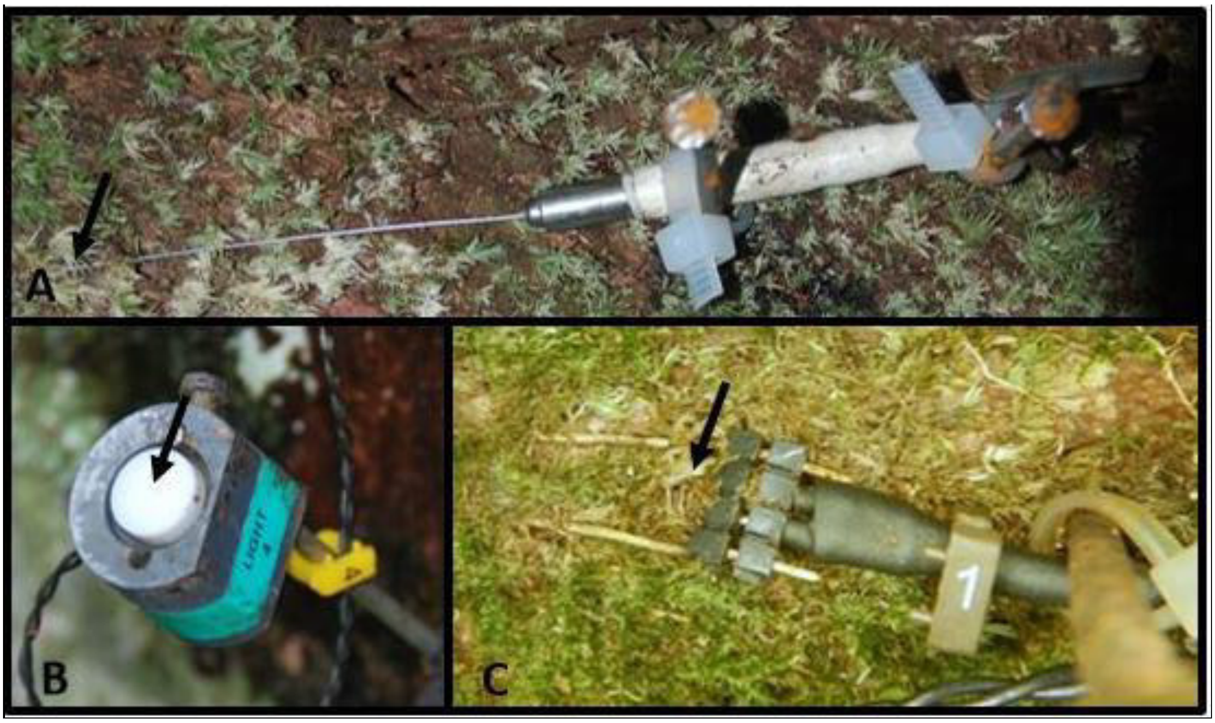


Figure S1: Examples of the temperature sensor (A), light sensor (B), and water content sensor (C) installed in epiphytic bryophytes at the ATTO site. The little arrows show the area of detection, i.e. the sensor tip of the temperature sensor, the area just below the white PTFE cap of the light sensor,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

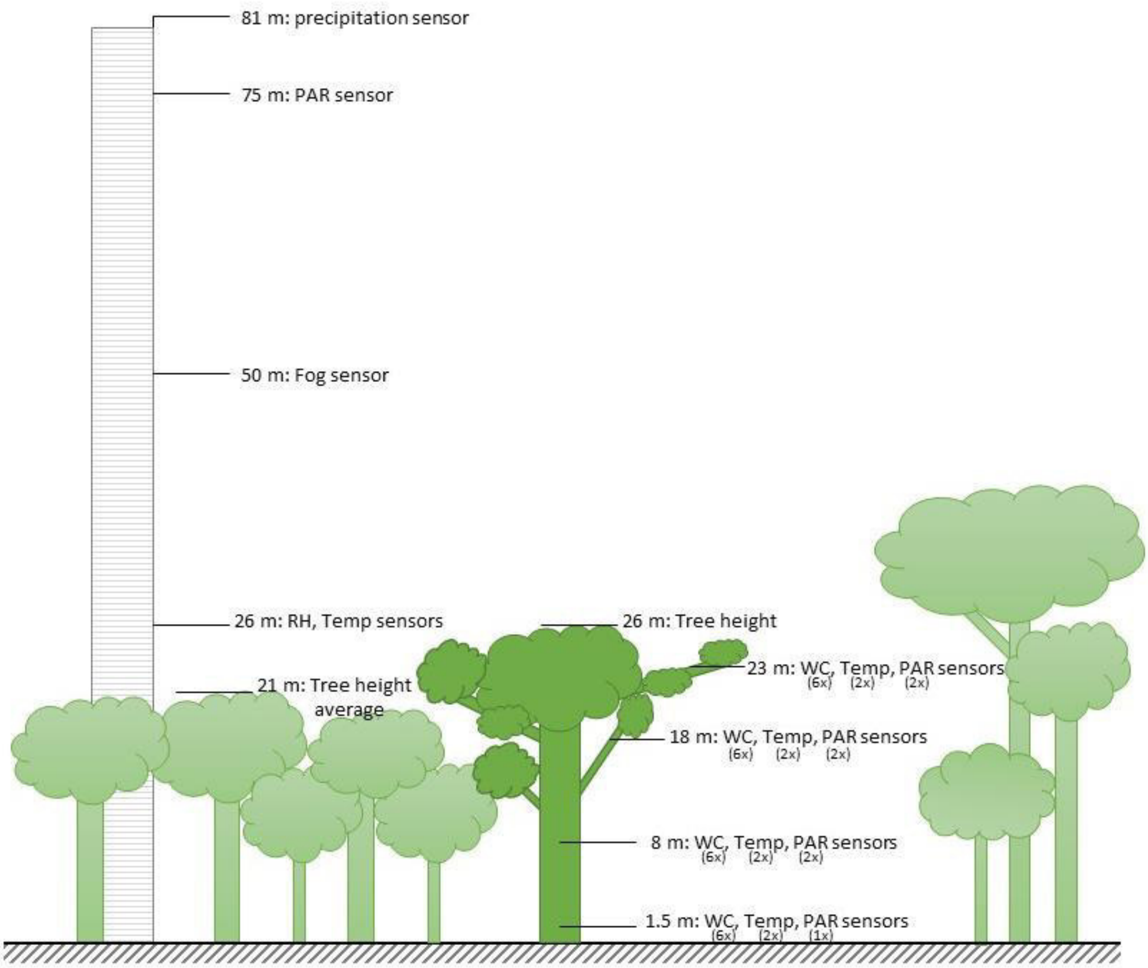


Figure S2: Schematic overview of the sensors installed at different height levels below, within, and above the canopy. The parameters water content (WC) and temperature (Temp) were measured within the bryophyte samples, the light sensors (PAR) were installed directly on top of the thalli. The average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

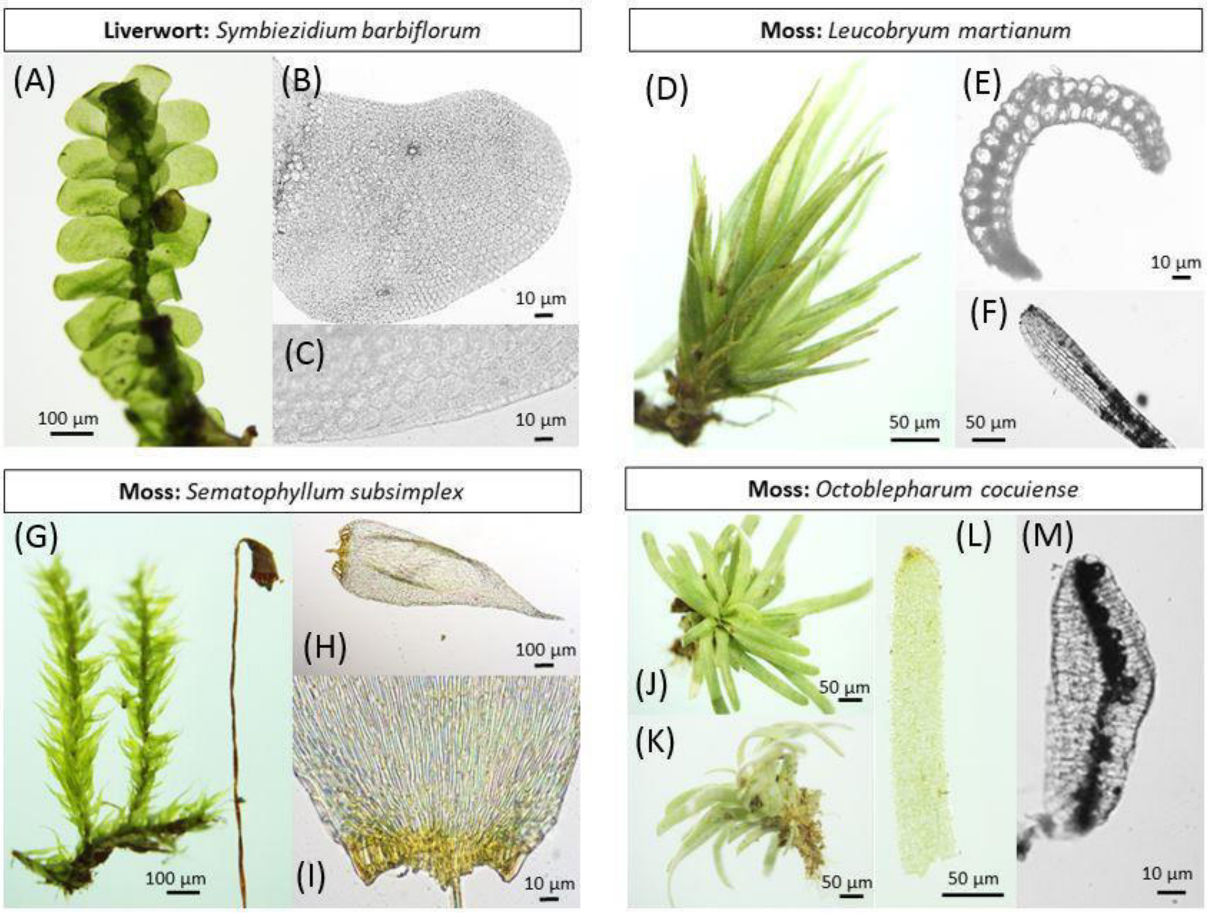
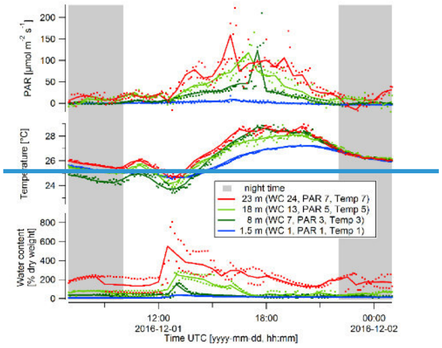


Figure S3: The four bryophyte species being used for installation of the sensors of the microclimate station. (A, D, G, J, K) overview, (B, H, L) leaf, (C, F I) cell form, and (E, M) cross section of a leaf.

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



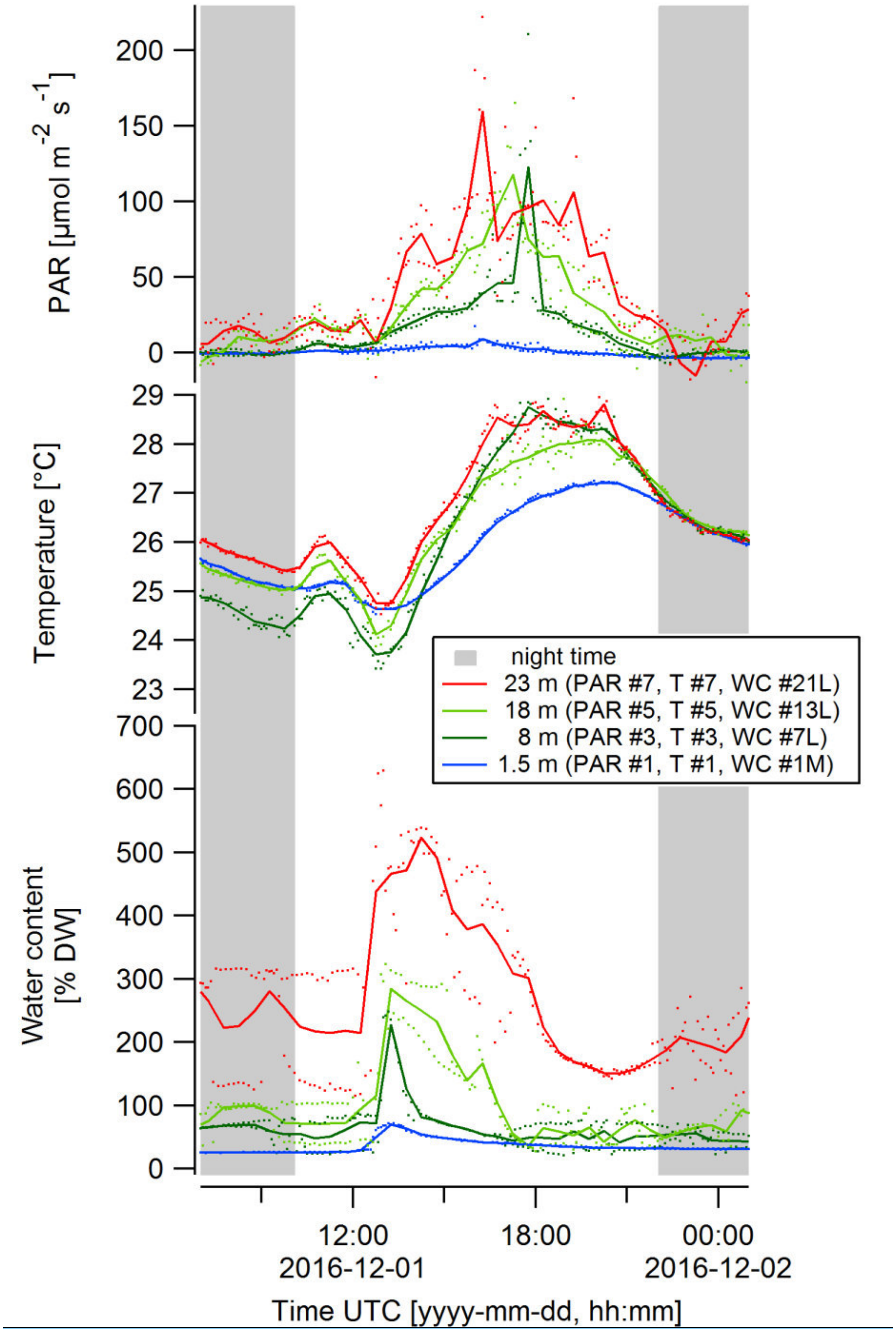
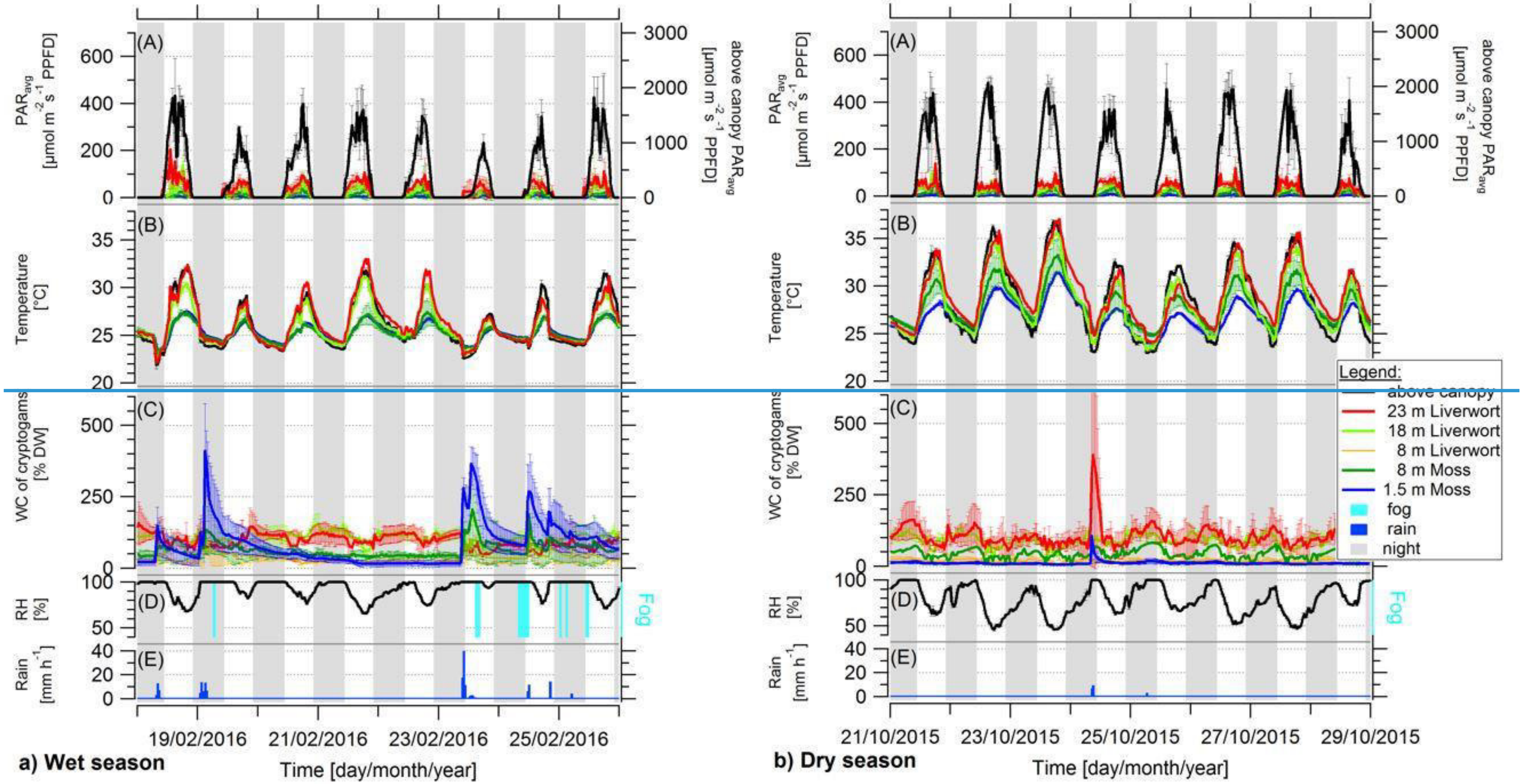
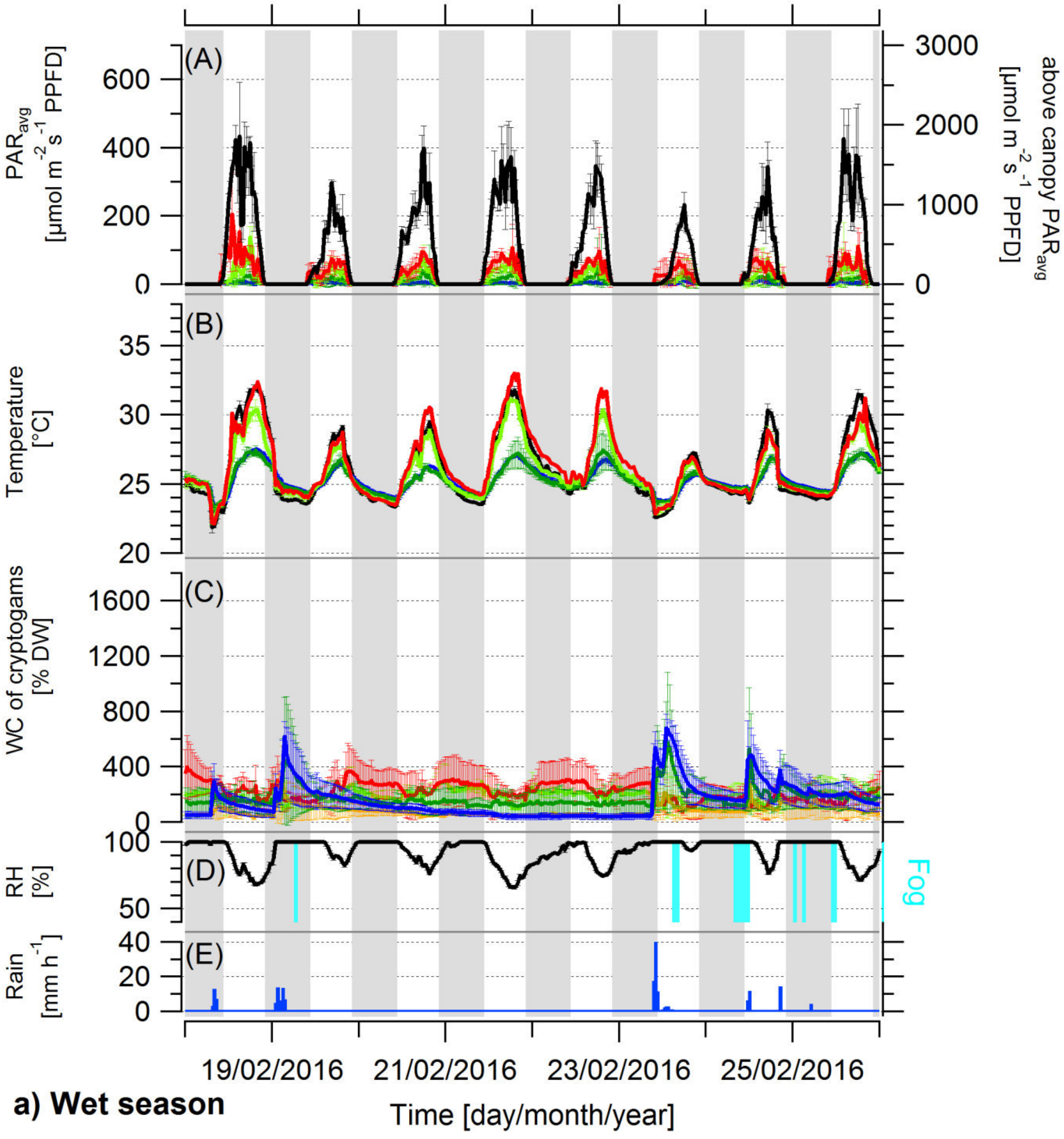


Figure S45: Comparison of 5-minute (dots) and 30-minute (lines) averages of exemplary sensors at each height level over a period of approx. one day in December 2016.


(A)
PAR$_{avg}$ [µmol m^{-2} s^{-1} PPFD]
above canopy PAR$_{avg}$ [µmol m^{-2} s^{-1} PPFD]
0
200
400
600
1000
2000
3000
(B)
Temperature [°C]
20
25
30
35
(C)
WC of cryptogams [% DW]
0
250
500
(D)
RH [%]
50
100
Fog
(E)
Rain [mm h^{-1}]
0
20
40
19/02/2016
21/02/2016
23/02/2016
25/02/2016
a) Wet season
21/10/2015
23/10/2015
25/10/2015
27/10/2015
29/10/2015
b) Dry season
Time [day/month/year]
Legend:
above canopy
23 m Liverwort
18 m Liverwort
8 m Liverwort
8 m Moss
1.5 m Moss
fog
rain
night


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

a) Wet season

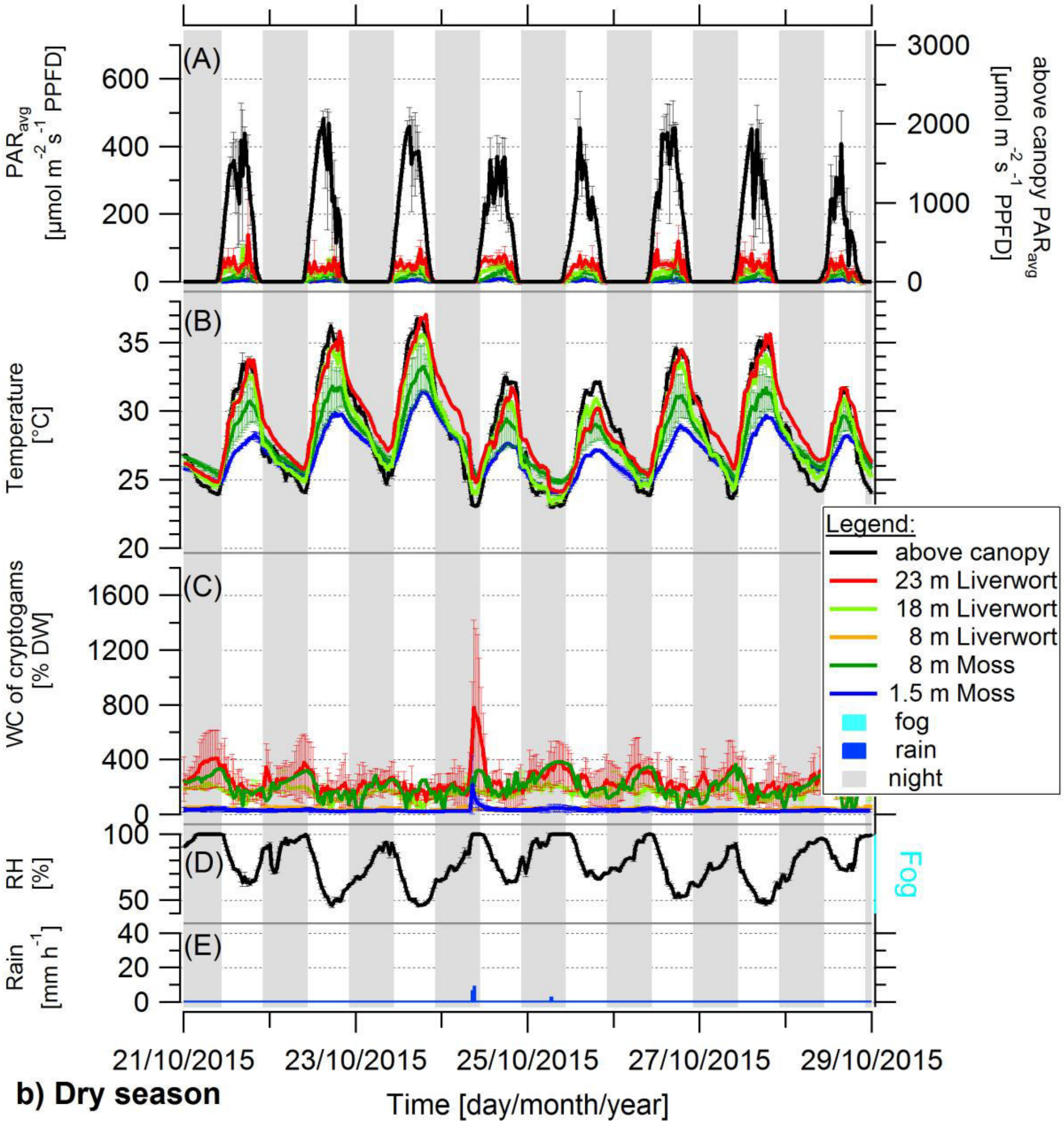
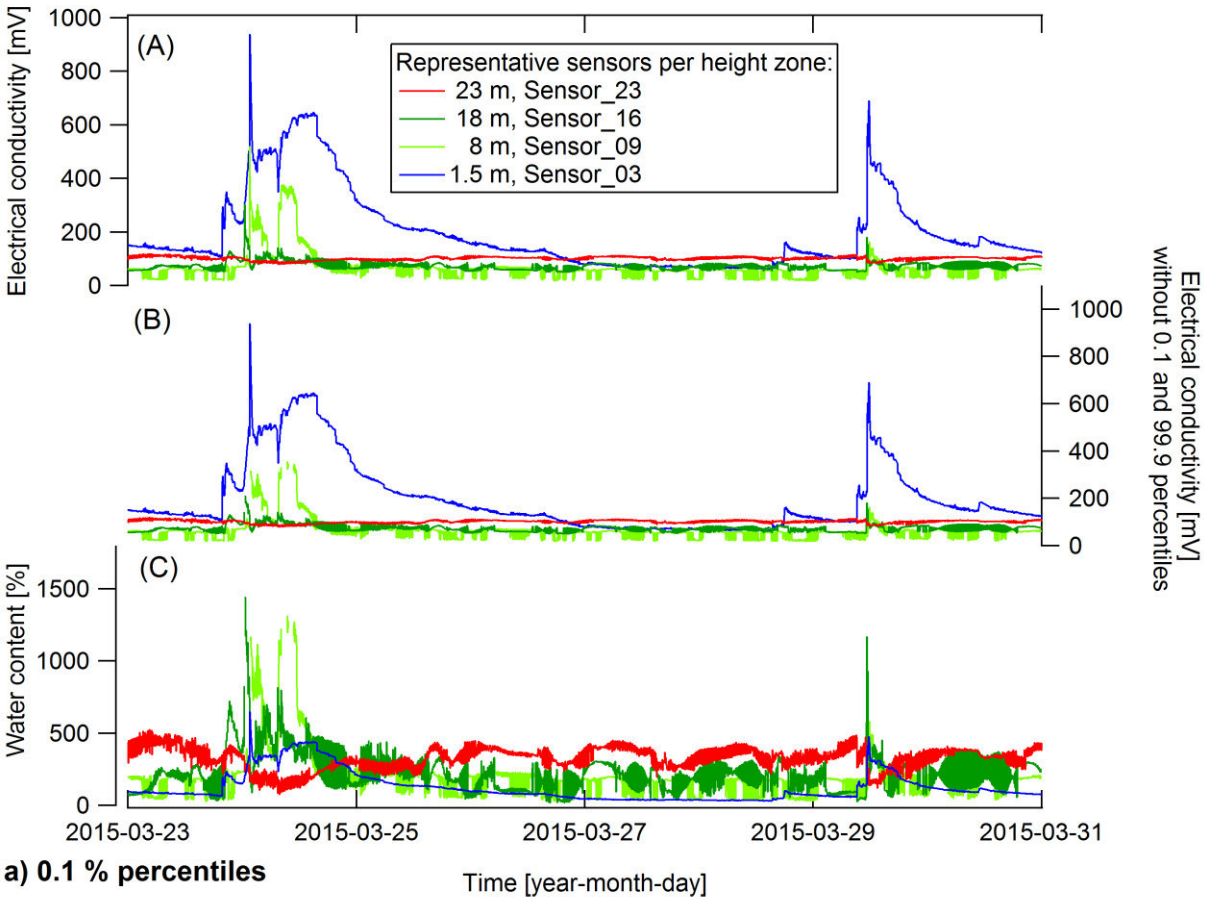
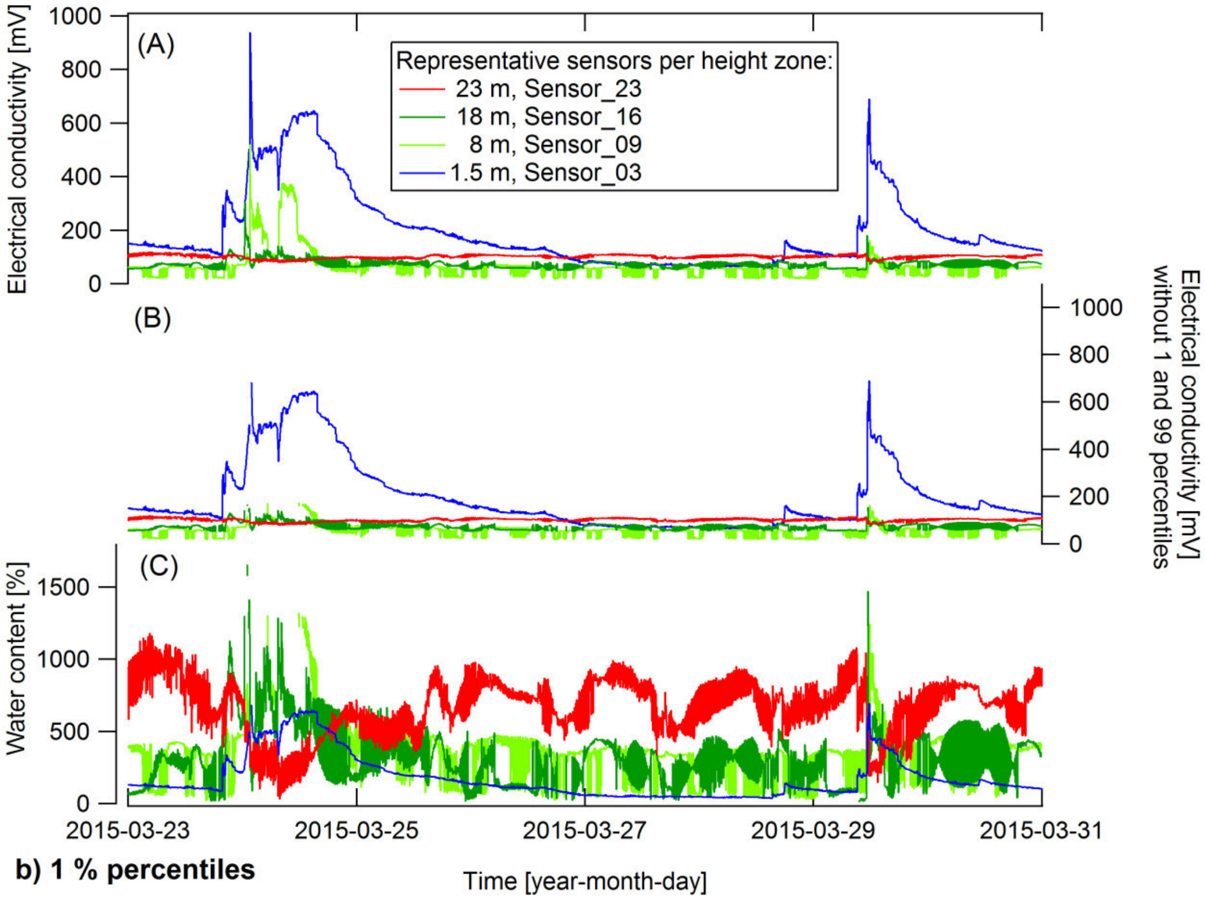


Figure S~~5~~6: Representative periods during wet and dry season under the influence of El Niño, showing light conditions (PAR$_{avg}$), temperature, and water content (WC)~~, temperature, and light conditions (PAR$_{avg}$)~~ experienced by bryophytes, and above-canopy meteorological conditions in the Amazonian rain forest. Shown are 8-day periods during a) the wet season 2016 and b) the dry season 2015. The micrometeorological parameters on top/within epiphytic cryptogamic communities represent (A) the photosynthetically active radiation (PAR$_{avg}$) 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 amount. The data show 30-minute averages ± SD except for rain, which shows hourly sums. Data of replicate sensors installed within communities at the same height level were pooled, while above-canopy parameters were measured with one sensor each. The night-time is shaded in grey color (06:00 – 18:00 LT).



a) 0.1 % percentiles



b) 1 % percentiles

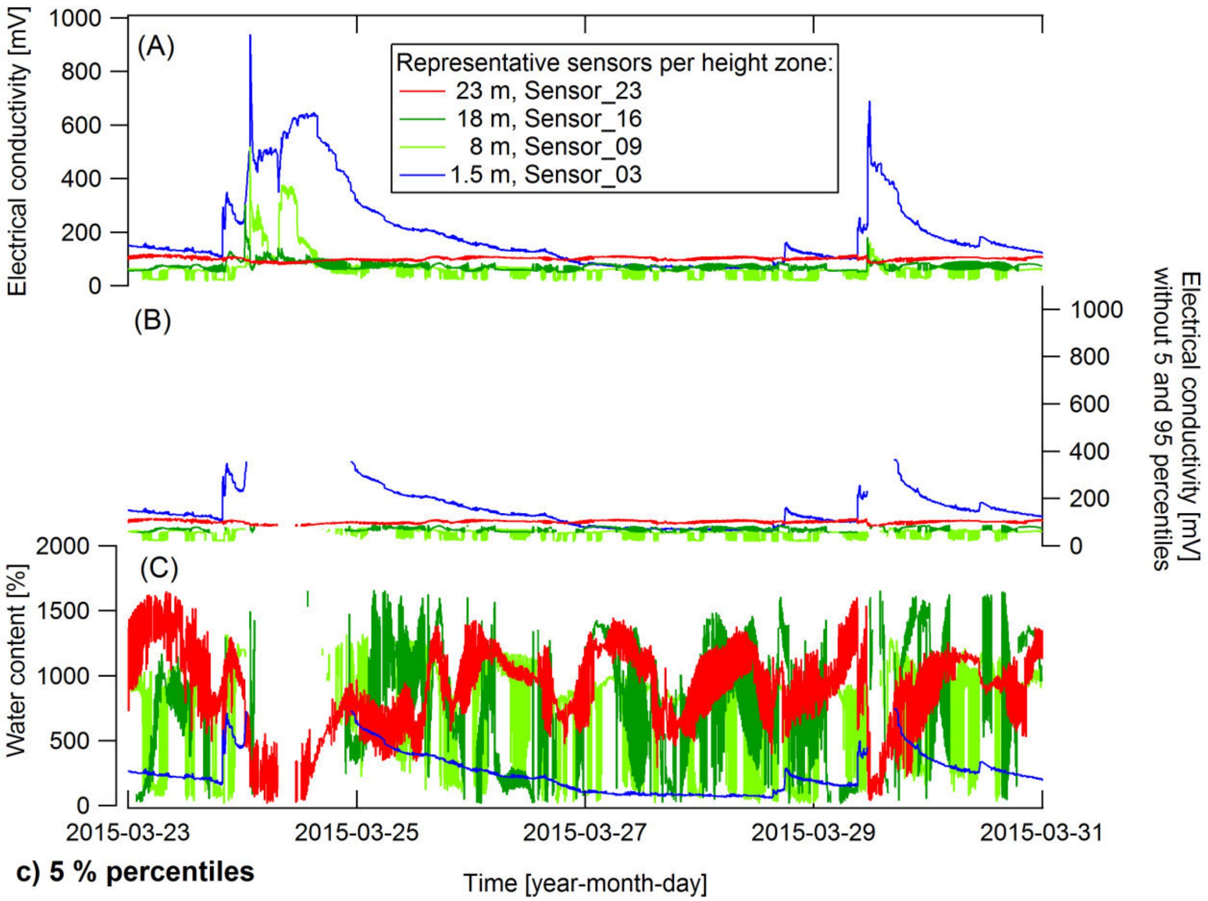
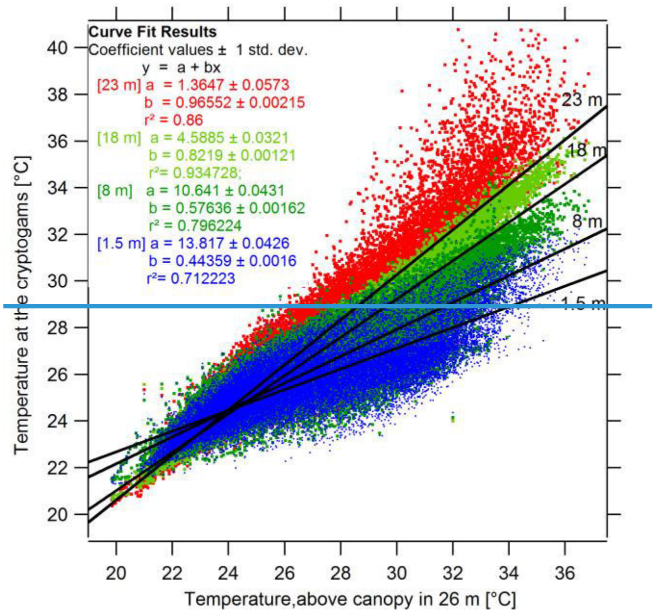


Figure S7: Exemplary snapshots of the conversion from (A) the measured electrical conductivity, via (B) the electrical conductivity minus the upper and the lower percentiles, to (C) the water content of the epiphytic bryophytes. The figures show a) the finally chosen 0.1 % percentiles, b) the 1 % percentiles,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



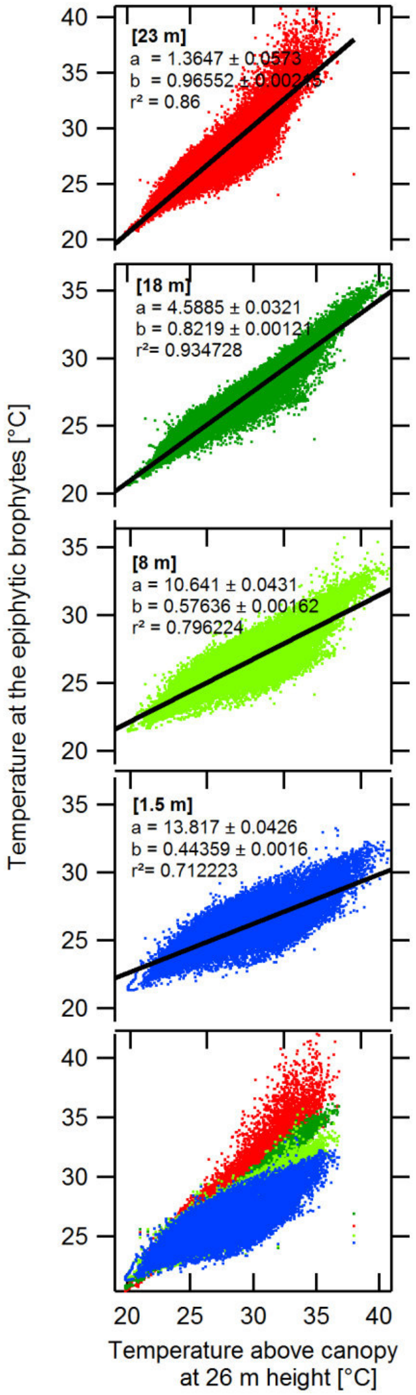
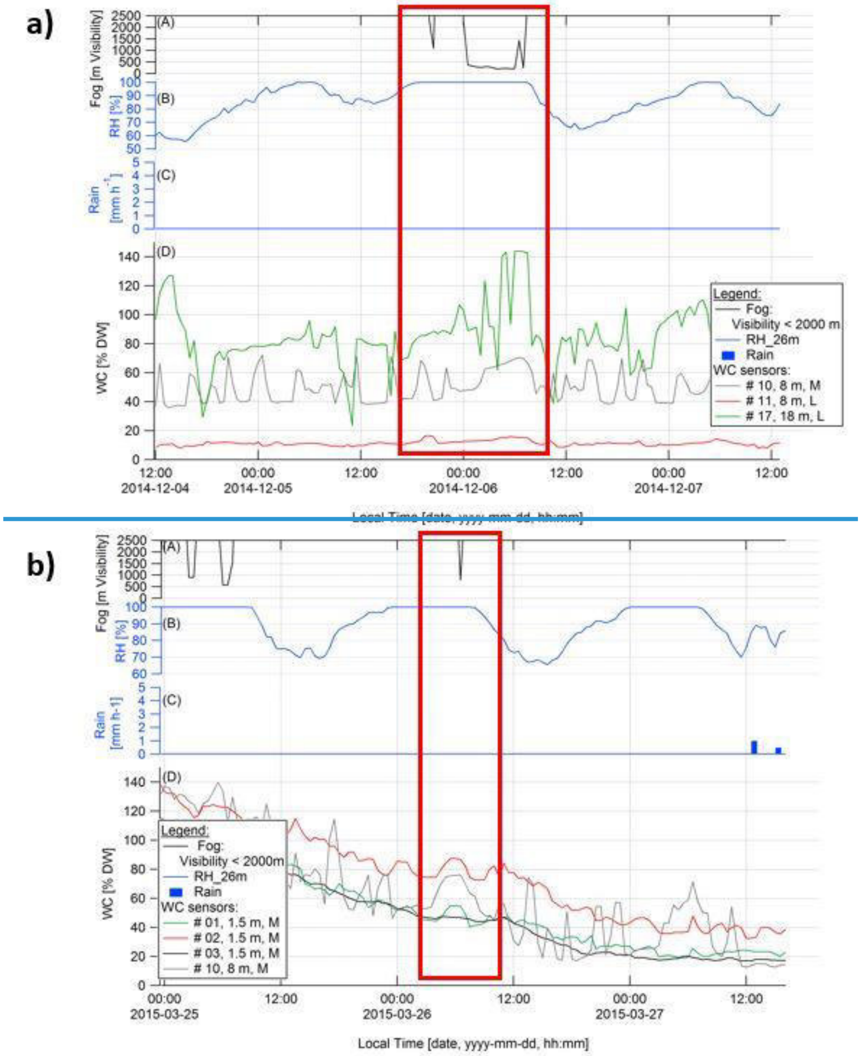


Figure S~~6~~8: Temperature within bryophytes compared to the above-canopy temperature. The temperature within bryophytes was measured at 1.5 m, 8 m, 18 m, and 23 m, while the above-canopy temperature was measured at 26 m height on the tower. The data are presented per height zone and also pooled together in the lowest panel. Data present 30-minute averages with linear fits, of the function y = a + bx, with ~~. For each height level~~ the coefficients (± 1 std. dev.) and the R² are given in the figure for each height level.



a)
Fog [m Visibility]
(A)
2500 2000 1500 1000 500 0
RH [%]
(B)
100 90 80 70 60 50
Rain [mm h-1]
(C)
5 4 3 2 1 0
WC [% DW]
(D)
140 120 100 80 60 40 20 0
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)
2500 2000 1500 1000 500 0
RH [%]
(B)
100 90 80 70 60
Rain [mm h-1]
(C)
5 4 3 2 1 0
WC [% DW]
(D)
140 120 100 80 60 40 20 0
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]

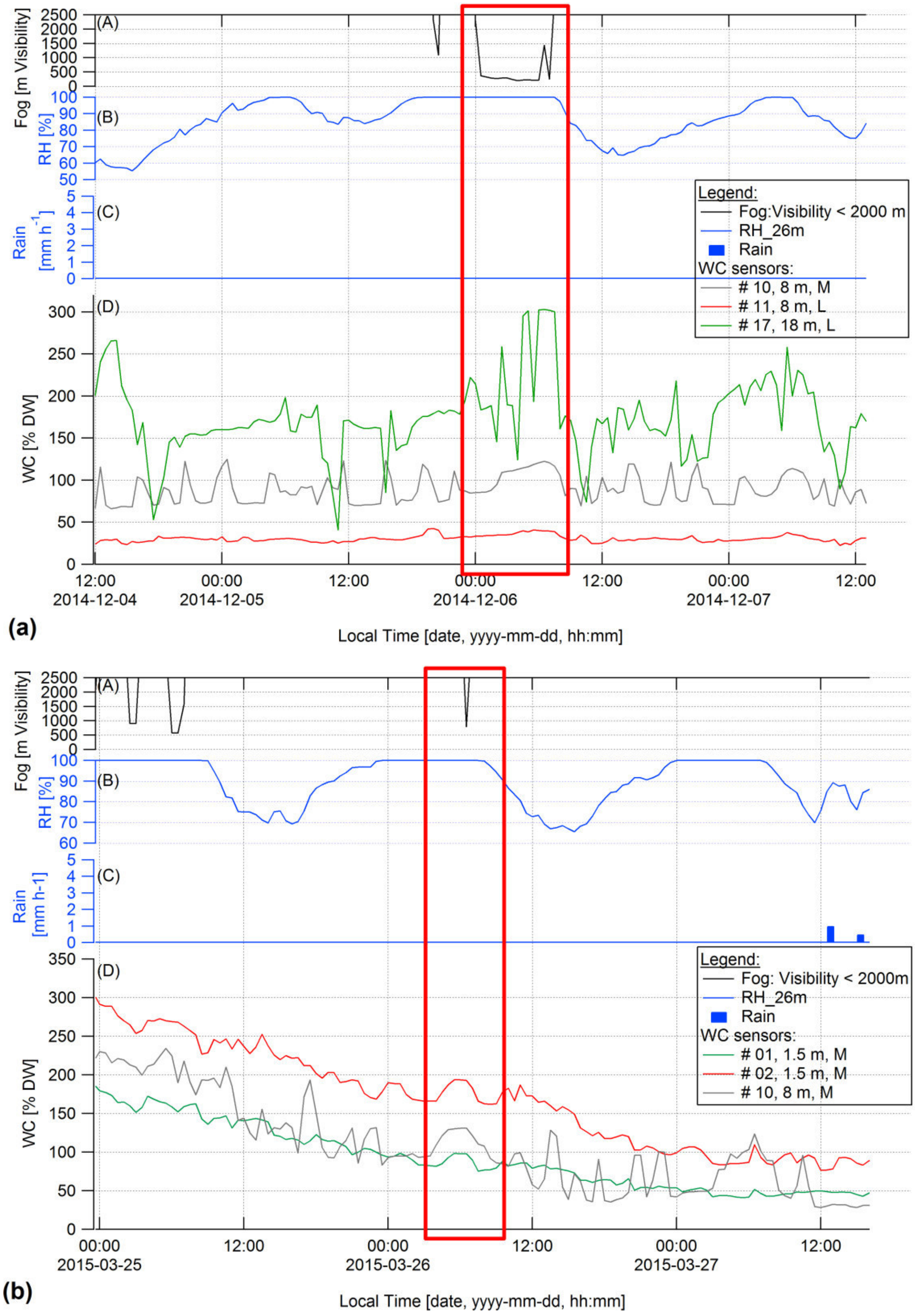


Figure S~~7~~9: Two exemplary fog events and the reaction of the moisture sensors of the bryophytes (a and b). Each panel presents (A) a fog event with the parameters fog with visibility < 2000 m being defined as fog occurrence, (B) relative air humidity (RH), (C) rain, and (D) the water content (WC) of the bryophytes shown for some exemplary sensors. The fog event of interest is marked by a red box. For the WC sensors the number, height of installation, and division (M = Moss, L = Liverwort) are given. Data presented as 30-minute averages.

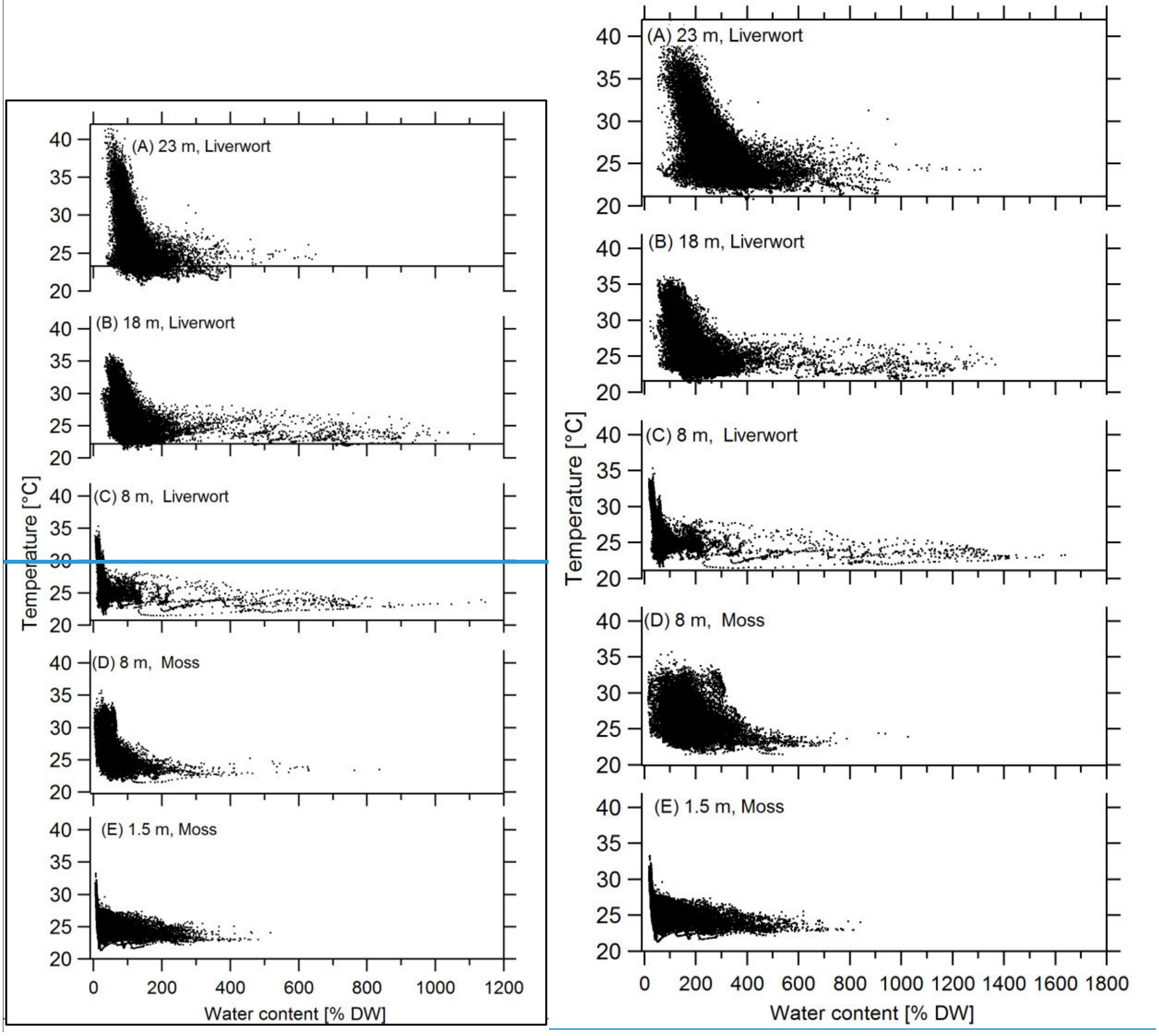


Figure S~~8~~10: Temperature conditions of bryophytes related to their water content. The temperature was measured in bryophytes at different height levels along the tree. Data presented as 30-minute averages.

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

Water content	Height [m]	WC [% DW] m~~M~~in (0.1%)	m~~M~~ax (99.9%)	Bryophyte species
Sensor 01	1.5	14~~1~~	762~~660~~	*Sematophyllum subsimplex*
Sensor 02	1.5	14~~1~~	761~~543~~	*Sematophyllum subsimplex*
Sensor 03	1.5	13~~0~~	761~~640~~	*Sematophyllum subsimplex*
Sensor 04	1.5	15~~3~~	1368~~639~~	*Leucobryum martianum*
Sensor 05	1.5	13~~5~~	760~~645~~	*Sematophyllum subsimplex*
Sensor 06	1.5	17~~3~~	750~~730~~	*Sematophyllum subsimplex*
Sensor 07	8	16~~1~~	1647~~1480~~	*Symbiezidium barbiflorum*
Sensor 08	8	15~~2~~	1311~~1066~~	*Octoblepharum cocuiense*
Sensor 09	8	15~~3~~	1302~~1223~~	*Octoblepharum cocuiense*
Sensor 10	8	16~~2~~	1315~~1075~~	*Octoblepharum cocuiense*
Sensor 11	8	17~~3~~	1649~~1262~~	*Symbiezidium barbiflorum*
Sensor 12	8	17~~6~~	1639~~1355~~	*Symbiezidium barbiflorum*
Sensor 13	18	19~~6~~	1657~~1584~~	*Symbiezidium barbiflorum*
Sensor 14	18	21~~17~~	1576~~1345~~	*Symbiezidium barbiflorum*
Sensor 15	18	20~~17~~	1637~~1552~~	*Symbiezidium barbiflorum*
Sensor 16	18	20~~13~~	1626~~1573~~	*Symbiezidium barbiflorum*
Sensor 17	18	18~~10~~	1655~~1342~~	*Symbiezidium barbiflorum*
Sensor 18	18	17~~0~~	1618~~1642~~	*Symbiezidium barbiflorum*
Sensor 19	23	22~~14~~	1598~~1283~~	*Symbiezidium barbiflorum*
Sensor 20	23			*Symbiezidium barbiflorum*
Sensor 21	23	22~~17~~	1484~~1252~~	*Symbiezidium barbiflorum*
Sensor 22	23	22~~13~~	1592~~1066~~	*Symbiezidium barbiflorum*
Sensor 23	23	29~~29~~	1653~~893~~	*Symbiezidium barbiflorum*
Sensor 24	23	17~~0~~	1654~~1725~~	*Symbiezidium barbiflorum*

Temperature	Height [m]	Temperature [°C] min	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	max
Sensor 01	1.5	0	634
Sensor 02	8	0	569
Sensor 03	8	0	1121
Sensor 04	18	0	525
Sensor 05	18	0	615
Sensor 06	23	0	654
Sensor 07	23	0	767

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

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

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

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

Table S~~2~~4: Monthly mean values and standard deviations (± SD) of photosynthetically active radiation (PAR_{avg} daytime, measured at 75 m), daily maxima of photosynthetically active radiation (PAR_{max}), temperature (measured at 26 m), and relative humidity (RH, measured at 26 m). Rainfall is presented as the monthly amounts and the percentage of days with rain (measured at 81 m), and also the percentage of days when rain detection malfunctioned are listed. Fog events are given as the percentage of days. Due to data gaps in the measured rain data (shown in brackets) values for 21 days of rain were also extrapolated from existing data as described in methods section (values behind data in brackets). Values were calculated from 30-minute intervals. Fog has not being recorded in the time ranges of 31.05. – 20.10.2015, 30.04. – 06.07.2016, 01.09. – 31.12.2016 due to malfunction of the device.

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

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

Table S~~3~~5: Parameters determining the time range of photosynthesis and respiration. The ranges of values defining the lower water compensation point (WCP), the lower light compensation point (LCP$_l$), the temperature for optimal net photosynthesis (T$_{opt}$), and the upper temperature compensation point (TCP) as relevant parameters have been extracted from published studies conducted at various study sites in the tropical rain forest.

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

Table S46: 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}]								PAR_{max} [µmol m^{-2} s^{-1}]							
	1.5 m		8 m		18 m		23 m		1.5 m		8 m		18 m		23 m	
	Mean	± SD	Mean	± SD	Mean	± SD	Mean	± SD	Mean	± SD	Mean	± SD	Mean	± SD	Mean	± SD
Oct 2014	4	8	30	31	55	63	88	90	75	105	285	231	465	369	624	286
Nov 2014	4	11	23	32	27	18	24	37	142	131	396	321	188	185	378	275
Dec 2014	6	18	31	50	52	28	25	33	236	172	435	228	201	173	346	235
Jan 2015	3	8	22	28	46	24	20	27	155	96	341	219	189	167	341	246
Feb 2015	2	3	31	21	52	25	16	17	46	33	173	183	187	139	234	244
Mar 2015	3	4	43	35	42	25	16	15	45	55	292	159	159	125	128	117
Apr 2015	6	20	80	105	48	41	16	18	346	310	480	231	351	232	241	231
May 2015	6	32	66	71	52	52	16	17	634	428	282	236	460	207	146	137
Jun 2015	2	3	73	64	55	55	18	20	42	51	214	125	404	139	177	141
Jul 2015	3	12	54	73	52	59	15	18	168	178	727	301	435	169	152	144
Aug 2015	13	56	66	115	52	71	24	23	601	414	746	193	521	161	227	170
Sep 2015	9	21	28	47	53	61	65	66	248	204	403	224	410	164	492	229
Oct 2015	3	4	15	15	32	28	44	30	53	47	128	99	226	147	221	157
Nov 2015	4	7	16	25	27	21	61	64	82	95	315	151	139	98	475	208
Dec 2015	5	11	22	35	29	19	88	103	112	116	308	171	145	113	645	250
Jan 2016	4	7	16	21	33	24	88	103	72	91	177	143	165	115	692	294
Feb 2016	3	4	13	11	30	26	57	46	46	54	79	76	167	159	388	237
Mar 2016	3	7	28	15	28	27	37	33	102	125	107	80	227	180	268	215
Apr 2016	5	15	27	19	29	46	38	31	192	199	59	27	481	208	270	203
May 2016	3	7	n.a.	n.a.	34	50	45	41	114	109	n.a.	n.a.	339	176	286	209
Jun 2016	2	2	n.a.	n.a.	28	41	58	68	25	34	n.a.	n.a.	301	129	416	199
Jul 2016	2	4	n.a.	n.a.	42	64	72	86	30	44	n.a.	n.a.	386	139	527	204
Aug 2016	9	34	31	52	46	74	71	94	319	216	340	241	477	130	614	256
Sep 2016	3	7	13	24	44	63	55	69	102	84	250	137	387	166	508	244
Oct 2016	2	3	7	9	43	61	47	54	35	28	106	71	428	241	421	219
Nov 2016	3	5	9	13	33	30	73	85	59	51	172	114	216	185	606	251
Dec 2016	4	12	24	38	24	19	52	56	156	131	361	282	117	96	457	274

Continuation of Table S~~4~~6

	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	186~~100~~	150~~86~~	215~~84~~	120~~67~~	59~~29~~	17~~8~~	201~~121~~	112~~67~~	350~~163~~	175~~7~~
Nov 14	25.3	1.2	25.7	1.4	25.9	1.8	26.2	2.3	57~~25~~	34~~18~~	150~~50~~	26~~11~~	56~~27~~	7~~3~~	182~~101~~	115~~58~~	342~~150~~	176~~6~~
Dec 14	25.4	1.1	25.8	1.3	26.1	1.6	26.6	2.1	70~~32~~	64~~34~~	157~~52~~	32~~14~~	56~~27~~	8~~4~~	186~~104~~	107~~55~~	268~~123~~	83~~33~~
Jan 15	24.2	1.1	24.3	1.3	24.5	1.7	24.6	1.8	151~~76~~	131~~72~~	189~~66~~	44~~20~~	60~~29~~	10~~5~~	183~~112~~	88~~59~~	302~~136~~	107~~4~~
Feb 15	24.5	1.0	24.5	1.1	25.0	2.0	25.0	1.8	124~~61~~	92~~50~~	181~~61~~	43~~20~~	59~~29~~	7~~4~~	170~~97~~	53~~30~~	335~~144~~	92~~32~~
Mar 15	24.4	0.9	24.3	0.9	24.6	1.6	24.5	1.3	153~~77~~	97~~52~~	212~~79~~	75~~38~~	68~~33~~	10~~5~~	217~~106~~	79~~40~~	352~~150~~	76~~27~~
Apr 15	24.6	0.9	24.7	1.1	25.0	1.8	24.9	1.8	107~~52~~	88~~51~~	169~~57~~	32~~15~~	61~~30~~	9~~5~~	229~~128~~	96~~58~~	294~~134~~	75~~27~~
May 15	24.6	0.9	24.5	0.9	24.8	1.7	24.8	1.7	159~~77~~	122~~63~~	230~~69~~	72~~29~~	59~~29~~	8~~4~~	192~~122~~	63~~37~~	290~~133~~	75~~27~~
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.~~	199~~126~~	30~~18~~	303~~138~~	77~~28~~
Jul 15	24.5	1.1	25.0	1.5	25.5	2.4	25.5	2.5	58~~25~~	31~~16~~	160~~60~~	43~~18~~	53~~25~~	10~~5~~	200~~127~~	37~~22~~	315~~145~~	142~~7~~
Aug 15	25.4	1.2	26.3	2.0	26.9	2.7	27.0	2.8	39~~15~~	14~~7~~	151~~51~~	36~~12~~	46~~21~~	9~~5~~	181~~102~~	49~~25~~	271~~125~~	98~~46~~
Sep 15	27.0	1.7	27.8	2.2	28.5	3.2	29.0	3.4	31~~11~~	25~~12~~	132~~45~~	36~~11~~	41~~19~~	10~~5~~	154~~87~~	44~~23~~	214~~103~~	111~~4~~
Oct 15	27.2	1.8	28.0	2.2	28.4	3.1	29.4	3.2	30~~11~~	19~~10~~	196~~42~~	74~~16~~	42~~20~~	10~~5~~	154~~88~~	48~~24~~	242~~106~~	139~~6~~
Nov 15	27.2	1.9	27.6	2.3	28.1	3.1	29.2	3.6	37~~14~~	21~~11~~	197~~42~~	74~~16~~	45~~21~~	19~~10~~	157~~89~~	43~~22~~	249~~108~~	118~~5~~
Dec 15	27.3	1.6	27.9	2.0	28.2	2.6	29.4	3.4	35~~13~~	15~~8~~	187~~40~~	72~~16~~	43~~20~~	15~~8~~	156~~89~~	43~~22~~	241~~104~~	104~~4~~
Jan 16	27.4	1.8	28.0	2.2	28.4	3.0	29.4	3.8	37~~14~~	21~~11~~	133~~42~~	51~~18~~	42~~19~~	16~~8~~	151~~86~~	47~~24~~	249~~108~~	105~~4~~
Feb 16	25.2	1.0	25.4	1.2	25.8	2.1	26.2	2.5	126~~66~~	120~~72~~	164~~60~~	83~~38~~	67~~31~~	39~~19~~	190~~105~~	52~~26~~	296~~124~~	111~~4~~
Mar 16	25.2	0.9	25.1	0.9	25.4	1.6	25.6	1.8	122~~61~~	96~~52~~	151~~56~~	59~~25~~	71~~33~~	30~~15~~	187~~119~~	50~~30~~	233~~106~~	73~~30~~
Apr 16	25.2	1.0	25.2	1.1	25.5	1.7	25.7	2.0	106~~52~~	64~~34~~	188~~75~~	83~~41~~	90~~41~~	47~~22~~	~~n.a.~~	~~n.a.~~	240~~108~~	85~~37~~
May 16	25.3	1.0	25.3	1.2	25.8	1.9	26.1	2.3	75~~35~~	47~~26~~	158~~59~~	59~~27~~	52~~21~~	26~~11~~	~~n.a.~~	~~n.a.~~	221~~100~~	74~~40~~
Jun 16	24.6	1.1	24.6	1.3	25.3	2.2	25.8	2.8	58~~25~~	25~~13~~	159~~58~~	62~~27~~	~~n.a.~~	~~n.a.~~	~~n.a.~~	~~n.a.~~	298~~111~~	85~~25~~
Jul 16	24.8	1.2	25.3	1.7	25.9	2.5	26.7	3.4	50~~21~~	28~~16~~	165~~45~~	64~~19~~	~~n.a.~~	~~n.a.~~	~~n.a.~~	~~n.a.~~	317~~117~~	130~~3~~
Aug 16	25.7	1.8	26.3	2.4	26.9	3.0	28.0	4.1	36~~14~~	31~~17~~	143~~46~~	75~~65~~	~~n.a.~~	~~n.a.~~	~~n.a.~~	~~n.a.~~	259~~100~~	86~~25~~
Sep 16	25.5	1.3	25.9	1.7	26.4	2.6	27.1	3.3	40~~16~~	38~~21~~	155~~43~~	73~~24~~	~~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	31~~11~~	9~~4~~	~~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	45~~19~~	32~~18~~	157~~60~~	118~~77~~	153~~87~~	242~~160~~	285~~162~~	215~~146~~	256~~117~~	95~~40~~
Dec 16	25.4	1.3	25.0	1.7	25.3	2.1	25.6	2.5	79~~39~~	67~~40~~	234~~83~~	134~~50~~	359~~207~~	372~~217~~	459~~295~~	319~~214~~	386~~176~~	167~~8~~

~~**Table S56:** Daily maximum values of the photosynthetically active radiation (PAR$_{max}$), the temperature (Temp$_{max}$), and the water content (WC$_{max}$) of epiphytic bryophytes. Mean values and standard deviations (± SD) are shown for dry and wet seasons of the two years 2015 and 2016. For the above canopy data maximum air humidity (RH) values measured at 26 m are shown, while for the bryophytes the water content was assessed. Above canopy light intensity was measured at 75 m, above canopy temperature and relative air humidity at 26 m. Data of the sensors installed at the same height level were pooled, while the above canopy parameters were measured with one sensor each.~~

-	~~**PAR$_{max}$ [µmol m^{-2} s^{-1}]**~~		~~**Temp$_{max}$ [°C]**~~		~~**RH$_{max}$ (above canopy), WC$_{max}$ [%]**~~	
~~**Season**~~	~~**Mean**~~	~~**± SD**~~	~~**Mean**~~	~~**± SD**~~	~~**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~~	~~262~~
~~Dry16~~	~~575~~	~~260~~	~~37.4~~	~~4.7~~	~~171~~	~~67~~
~~Wet15~~	~~167~~	~~202~~	~~28.4~~	~~2.5~~	~~175~~	~~43~~
~~Wet16~~	~~329~~	~~223~~	~~31.8~~	~~3.2~~	~~160~~	~~73~~
~~18 m Liverwort~~					-	-
~~Dry15~~	~~381~~	~~207~~	~~33.3~~	~~2.0~~	~~126~~	~~16~~
~~Dry16~~	~~443~~	~~204~~	~~32.8~~	~~2.2~~	~~252~~	~~274~~
~~Wet15~~	~~274~~	~~208~~	~~28.4~~	~~1.9~~	~~169~~	~~112~~
~~Wet16~~	~~289~~	~~188~~	~~29.6~~	~~1.7~~	~~144~~	~~89~~
~~8 m Liverwort~~						
~~Dry15~~					~~29~~	~~14~~
~~Dry16~~					~~232~~	~~377~~
~~Wet15~~					~~36~~	~~12~~
~~Wet16~~					~~62~~	~~96~~
~~8 m Moss~~					-	-
~~Dry15~~	~~414~~	~~381~~	~~32.0~~	~~3.2~~	~~68~~	~~13~~
~~Dry16~~	~~175~~	~~258~~	~~31.0~~	~~3.9~~	~~65~~	~~8~~
~~Wet15~~	~~246~~	~~395~~	~~26.5~~	~~1.5~~	~~98~~	~~65~~
~~Wet16~~	~~44~~	~~88~~	~~27.8~~	~~1.8~~	~~103~~	~~92~~
~~1.5 m Moss~~					-	-
~~Dry15~~	~~290~~	~~369~~	~~29.3~~	~~1.6~~	~~25~~	~~42~~
~~Dry16~~	~~127~~	~~173~~	~~29.0~~	~~2.5~~	~~33~~	~~100~~
~~Wet15~~	~~132~~	~~284~~	~~26.0~~	~~1.0~~	~~113~~	~~102~~
~~Wet16~~	~~96~~	~~140~~	~~27.0~~	~~1.0~~	~~116~~	~~100~~

~~**Table S67:** Daily amplitudes of the photosynthetically active radiation (PAR$_{amp}$), the temperature (Temp$_{amp}$), and the water content (WC$_{amp}$) of epiphytic bryophytes. Mean values and standard deviations (± SD) are shown for dry and wet seasons of the two years 2015 and 2016. For the above canopy data maximum air humidity (RH) values measured at 26 m are shown, while for the bryophytes the water content was assessed. Above canopy light intensity was measured at 75 m, above canopy temperature and relative air humidity at 26 m. Data of the sensors installed at the same height level were pooled, while the above canopy parameters were measured with one sensor each.~~

~~-~~	~~**PAR$_{amp}$ [µmol m^{-2} s^{-1}]**~~		~~**Temp$_{amp}$ [°C]**~~		~~**RH$_{amp}$ (above canopy), WC$_{amp}$ [%]**~~	
~~**Season**~~	~~**Mean**~~	~~**± SD**~~	~~**Mean**~~	~~**± SD**~~	~~**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~~	~~132~~	~~258~~
~~Dry16~~	~~575~~	~~260~~	~~13.2~~	~~4.5~~	~~109~~	~~65~~
~~Wet15~~	~~167~~	~~202~~	~~5.3~~	~~2.4~~	~~73~~	~~43~~
~~Wet16~~	~~329~~	~~223~~	~~8.1~~	~~3.1~~	~~95~~	~~71~~
~~18 m Liverwort~~						~~-~~
~~Dry15~~	~~381~~	~~207~~	~~9.3~~	~~1.6~~	~~70~~	~~21~~
~~Dry16~~	~~443~~	~~204~~	~~9.1~~	~~1.9~~	~~176~~	~~269~~
~~Wet15~~	~~274~~	~~208~~	~~5.5~~	~~1.8~~	~~112~~	~~98~~
~~Wet16~~	~~289~~	~~188~~	~~6.0~~	~~1.7~~	~~72~~	~~37~~
~~8 m Liverwort~~						
~~Dry15~~					~~18~~	~~13~~
~~Dry16~~					~~240~~	~~396~~
~~Wet15~~					~~11~~	~~6~~
~~Wet16~~					~~41~~	~~56~~
~~8 m Moss~~						
~~Dry15~~	~~414~~	~~381~~	~~7.0~~	~~3.2~~	~~45~~	~~19~~
~~Dry16~~	~~175~~	~~258~~	~~6.8~~	~~3.9~~	~~54~~	~~8~~
~~Wet15~~	~~246~~	~~395~~	~~3.1~~	~~1.4~~	~~58~~	~~64~~
~~Wet16~~	~~44~~	~~88~~	~~3.7~~	~~1.9~~	~~68~~	~~83~~
~~1.5 Moss~~					~~-~~	~~-~~
~~Dry15~~	~~290~~	~~369~~	~~4.4~~	~~1.2~~	~~16~~	~~41~~
~~Dry16~~	~~127~~	~~173~~	~~4.9~~	~~2.4~~	~~23~~	~~88~~
~~Wet15~~	~~132~~	~~284~~	~~2.5~~	~~1.0~~	~~73~~	~~89~~
~~Wet16~~	~~96~~	~~140~~	~~2.8~~	~~1.0~~	~~85~~	~~88~~

~~**Table S78:** Daily minimum values of the photosynthetically active radiation (PAR$_{min}$), the temperature (Temp$_{min}$), and the water content (WC$_{min}$) of epiphytic bryophytes. Mean values and standard deviations (± SD) are shown for dry and wet seasons of the two years 2015 and 2016. For the above-canopy data maximum air humidity (RH) values measured at 26 m are shown, while for the bryophytes the water content was assessed. Above-canopy light intensity was measured at 75 m, above canopy temperature and relative air humidity at 26 m. Data of the sensors installed at the same height level were pooled, while the above canopy parameters were measured with one sensor each.~~

-	~~**PAR$_{min}$ [µmol m^{-2} s^{-1}]**~~		~~**Temp$_{min}$ [°C]**~~		~~**RH$_{min}$ (above canopy), WC [%]**~~	
~~**Season**~~	~~**Mean**~~	~~**± SD**~~	~~**Mean**~~	~~**± SD**~~	~~**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~~	~~18~~
~~Dry16~~	~~0~~	~~0~~	~~24.1~~	~~1.3~~	~~59~~	~~19~~
~~Wet15~~	~~0~~	~~0~~	~~23.1~~	~~0.7~~	~~102~~	~~18~~
~~Wet16~~	~~0~~	~~0~~	~~23.6~~	~~0.6~~	~~66~~	~~23~~
~~18 m Liverwort~~					-	-
~~Dry15~~	~~0~~	~~0~~	~~24.0~~	~~1.0~~	~~55~~	~~23~~
~~Dry16~~	~~0~~	~~0~~	~~23.7~~	~~1.0~~	~~89~~	~~82~~
~~Wet15~~	~~0~~	~~0~~	~~22.9~~	~~0.6~~	~~57~~	~~34~~
~~Wet16~~	~~0~~	~~0~~	~~23.6~~	~~0.6~~	~~72~~	~~25~~
~~8 m Liverwort~~						
~~Dry15~~					~~11~~	~~4~~
~~Dry16~~					~~26~~	~~23~~
~~Wet15~~					~~25~~	~~10~~
~~Wet16~~					~~20~~	~~13~~
~~8 m Moss~~						
~~Dry15~~	~~0~~	~~0~~	~~25.0~~	~~1.0~~	~~24~~	~~13~~
~~Dry16~~	~~0~~	~~0~~	~~24.2~~	~~0.9~~	~~10~~	~~7~~
~~Wet15~~	~~0~~	~~0~~	~~23.4~~	~~0.5~~	~~41~~	~~18~~
~~Wet16~~	~~0~~	~~0~~	~~24.0~~	~~0.5~~	~~35~~	~~21~~
~~1.5 m Moss~~					-	-
~~Dry15~~	~~0~~	~~0~~	~~24.8~~	~~1.0~~	~~9~~	~~6~~
~~Dry16~~	~~0~~	~~0~~	~~24.1~~	~~0.9~~	~~10~~	~~28~~
~~Wet15~~	~~0~~	~~0~~	~~23.5~~	~~0.5~~	~~40~~	~~30~~
~~Wet16~~	~~0~~	~~0~~	~~24.1~~	~~0.5~~	~~31~~	~~29~~

Exemplary results for the percentiles 1 and 99

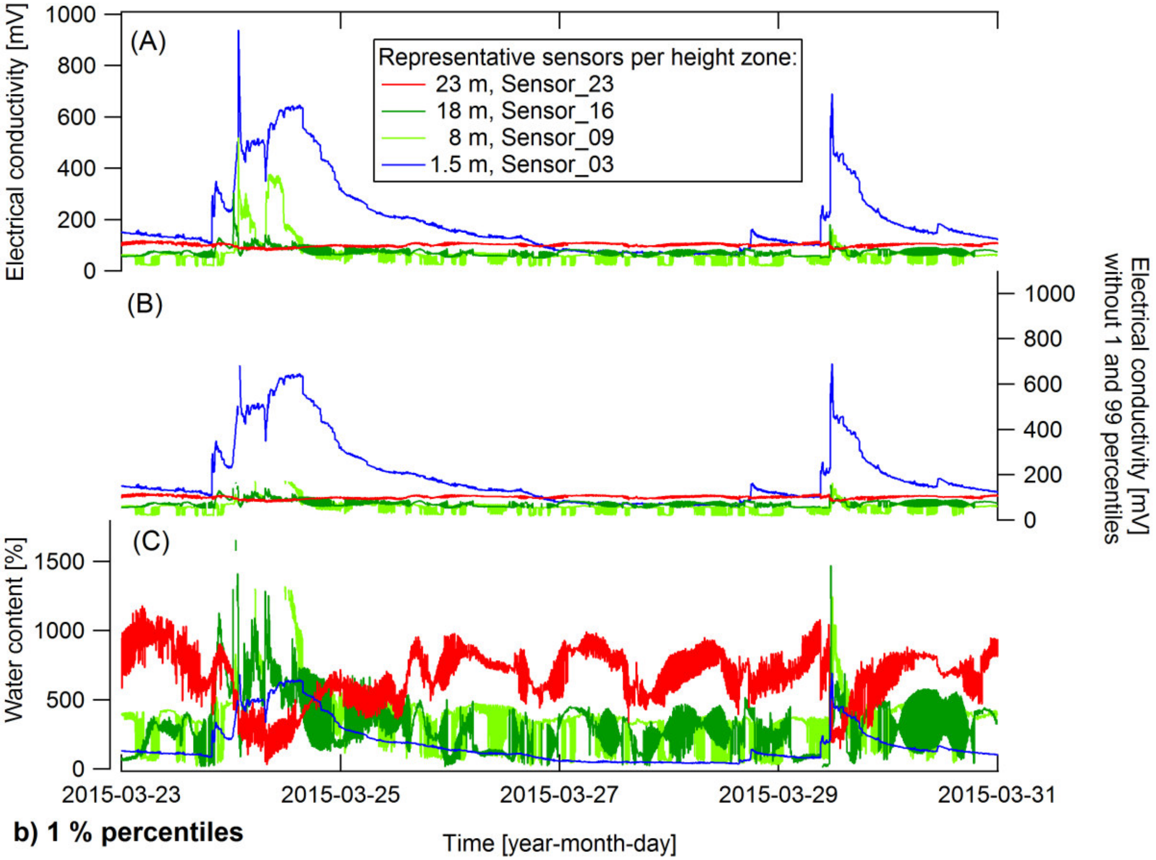
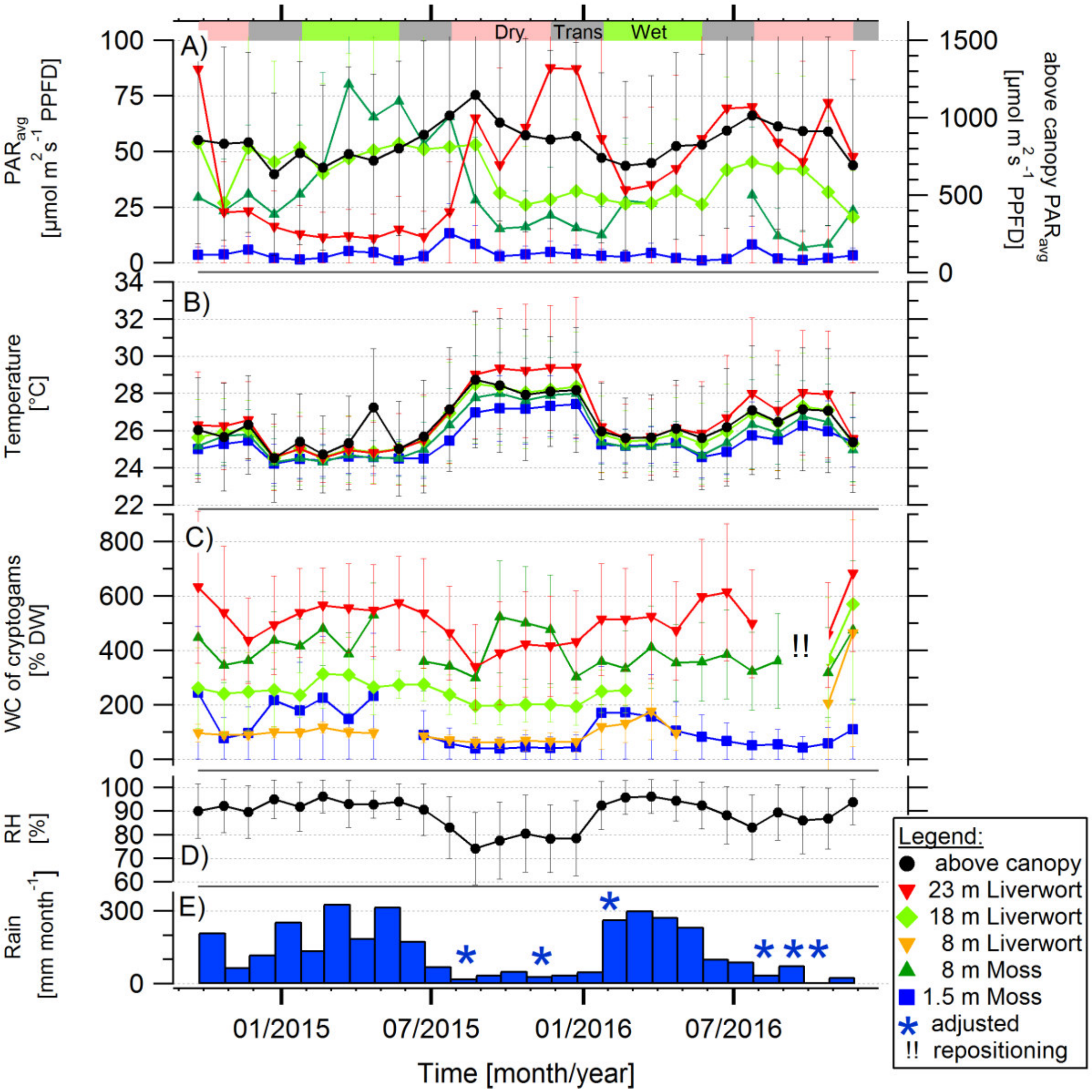


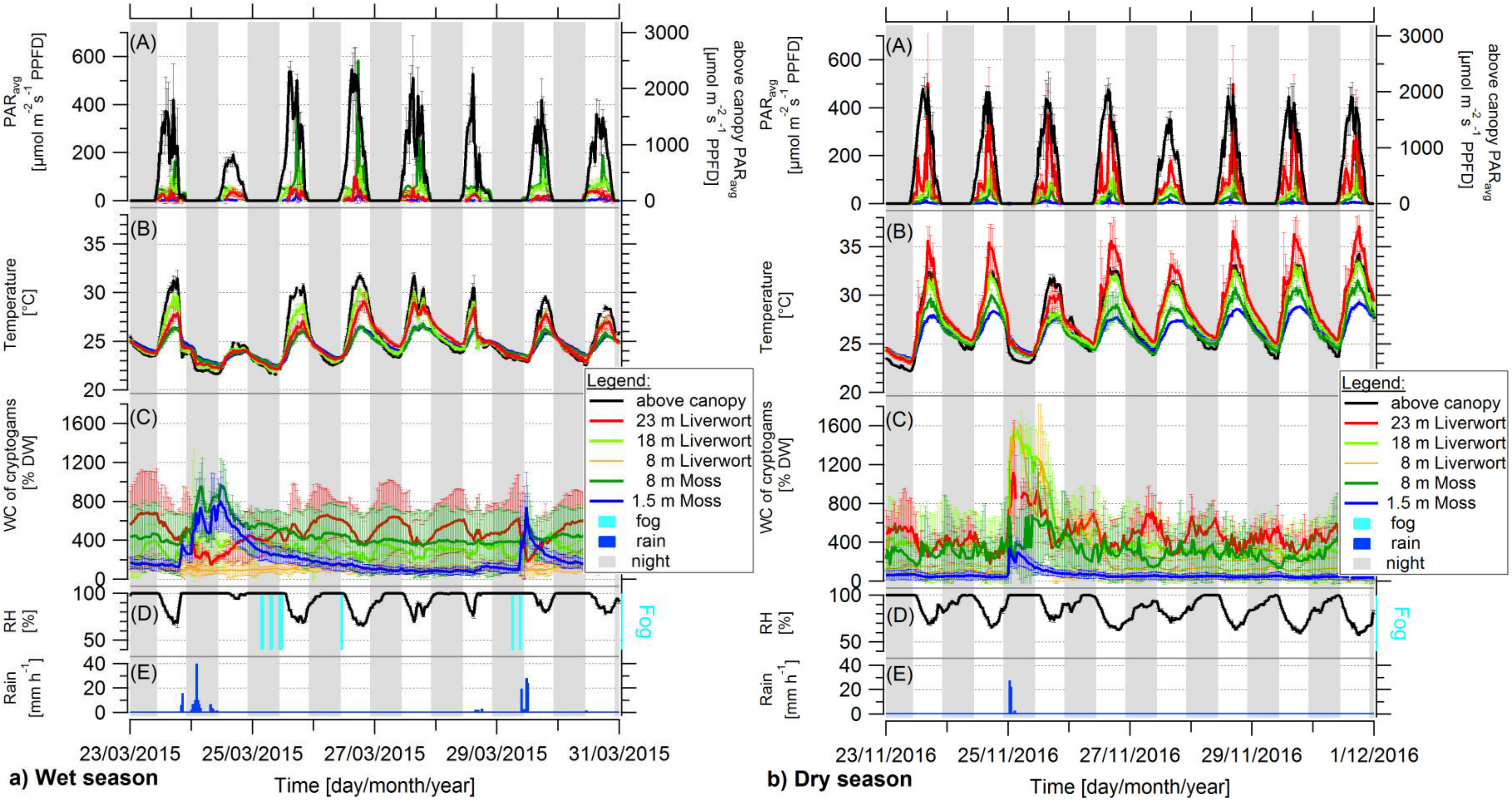
Figure S7 b): Exemplary snapshots of the conversion from (A) the measured electrical conductivity, via (B) the electrical conductivity minus the upper and the lower percentiles, to (C) the water content of the epiphytic bryophytes. The figure shows b) the 1 % percentiles (from Figure S7 of the Manuscript).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

Figure 1



Exemplary results for the percentiles 1 and 99

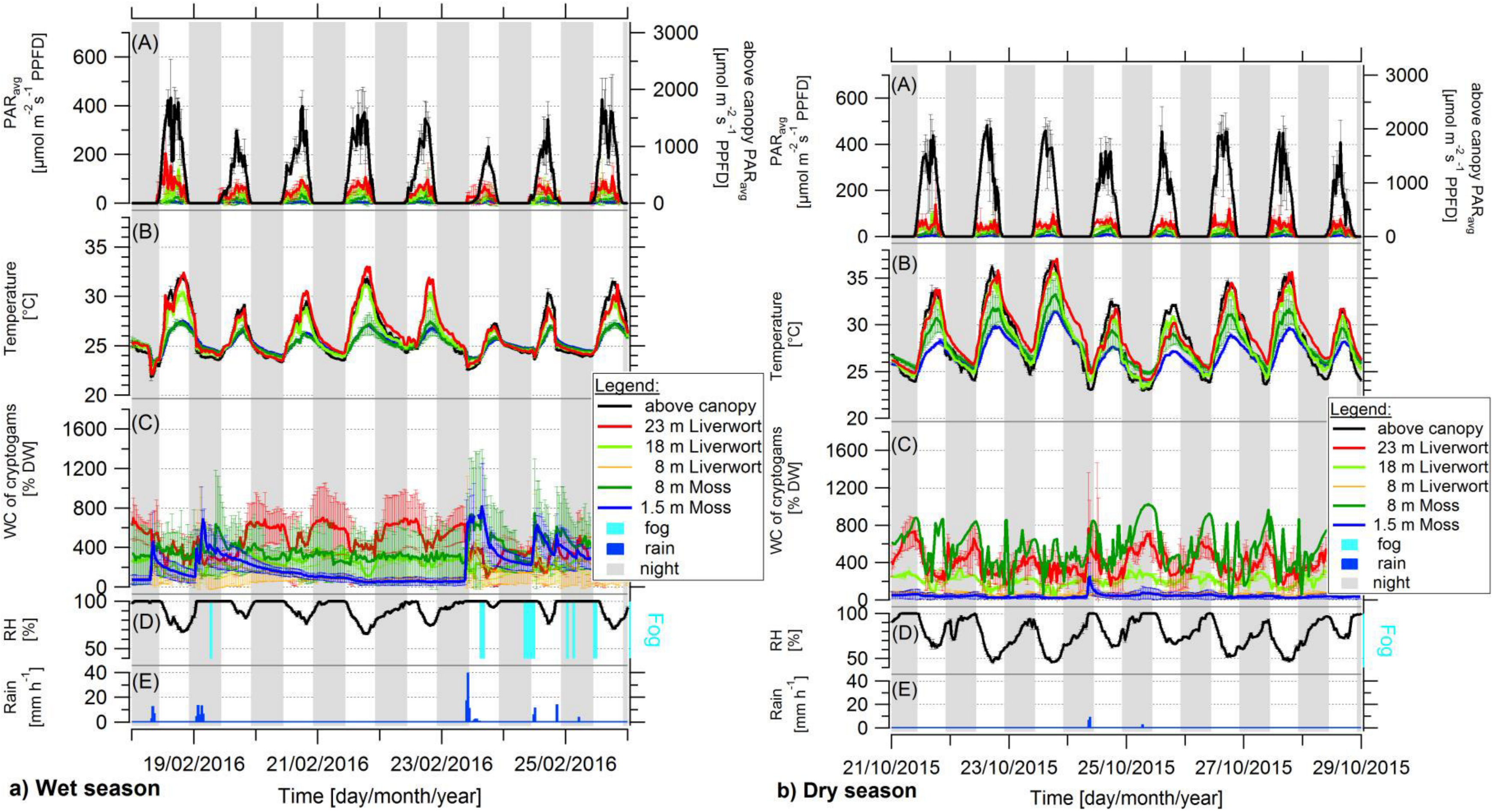
Fig 2“Normal Year”:



a) Wet season

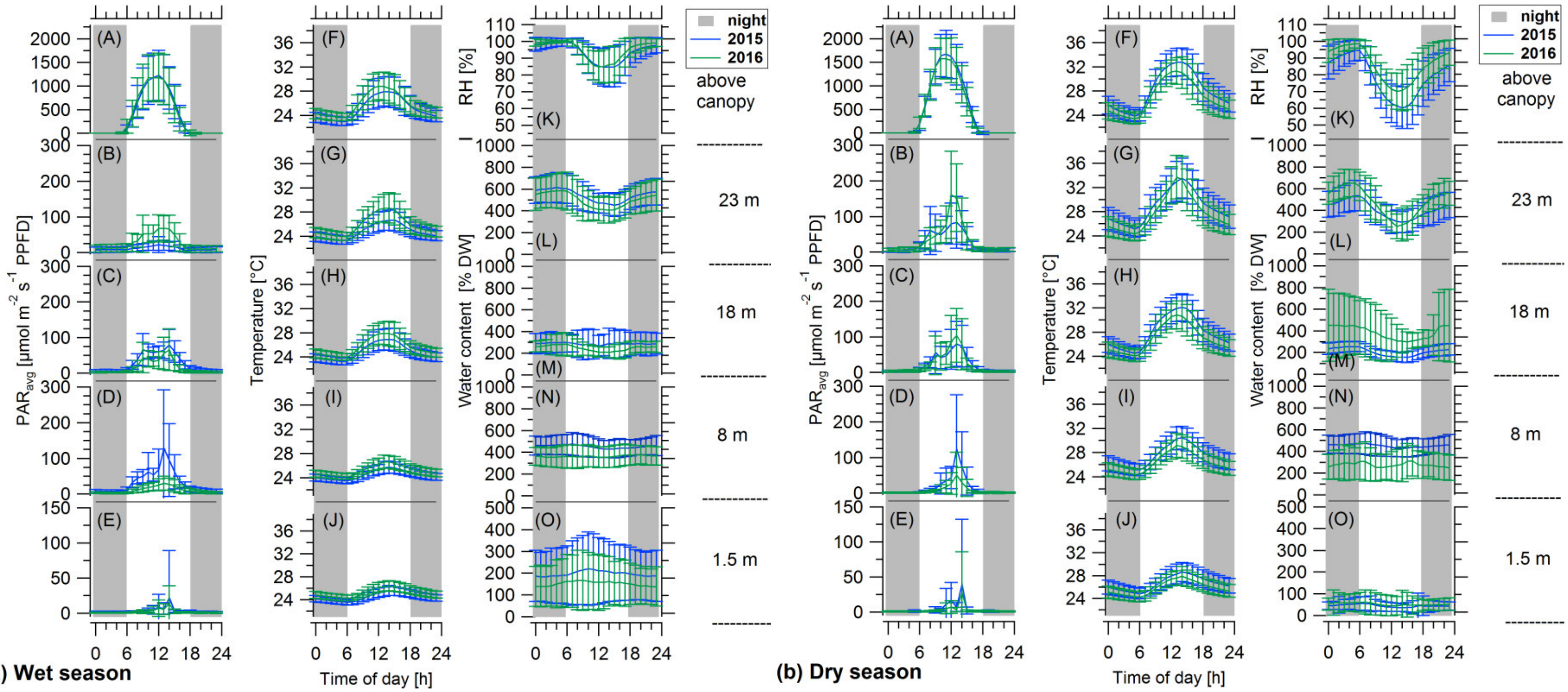
b) Dry season

Fig. S6 “El Nino Year”



Exemplary results for the percentiles 1 and 99

Figure 3:

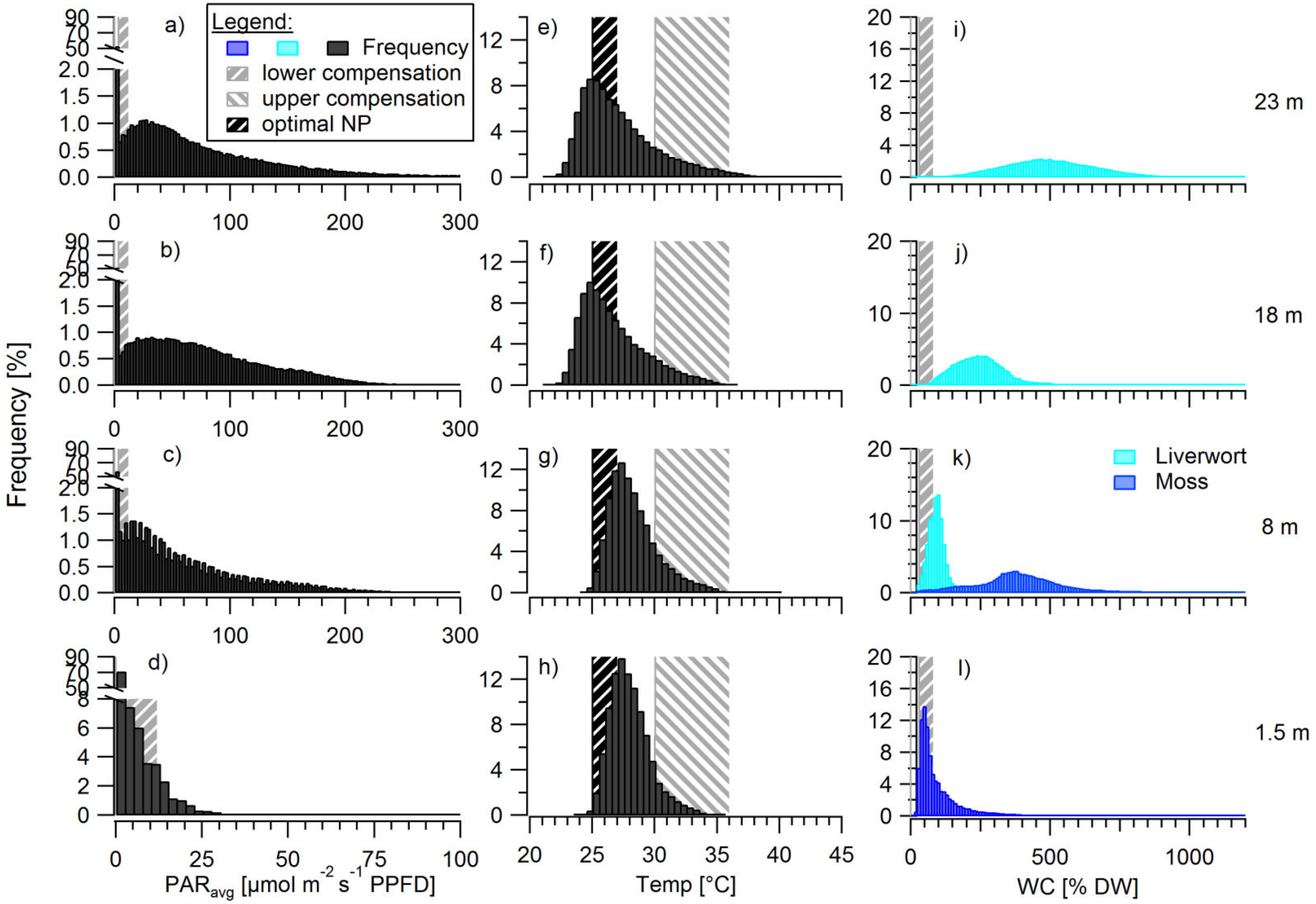


(a) Wet season **(b) Dry season**

Exemplary results for the percentiles 1 and 99

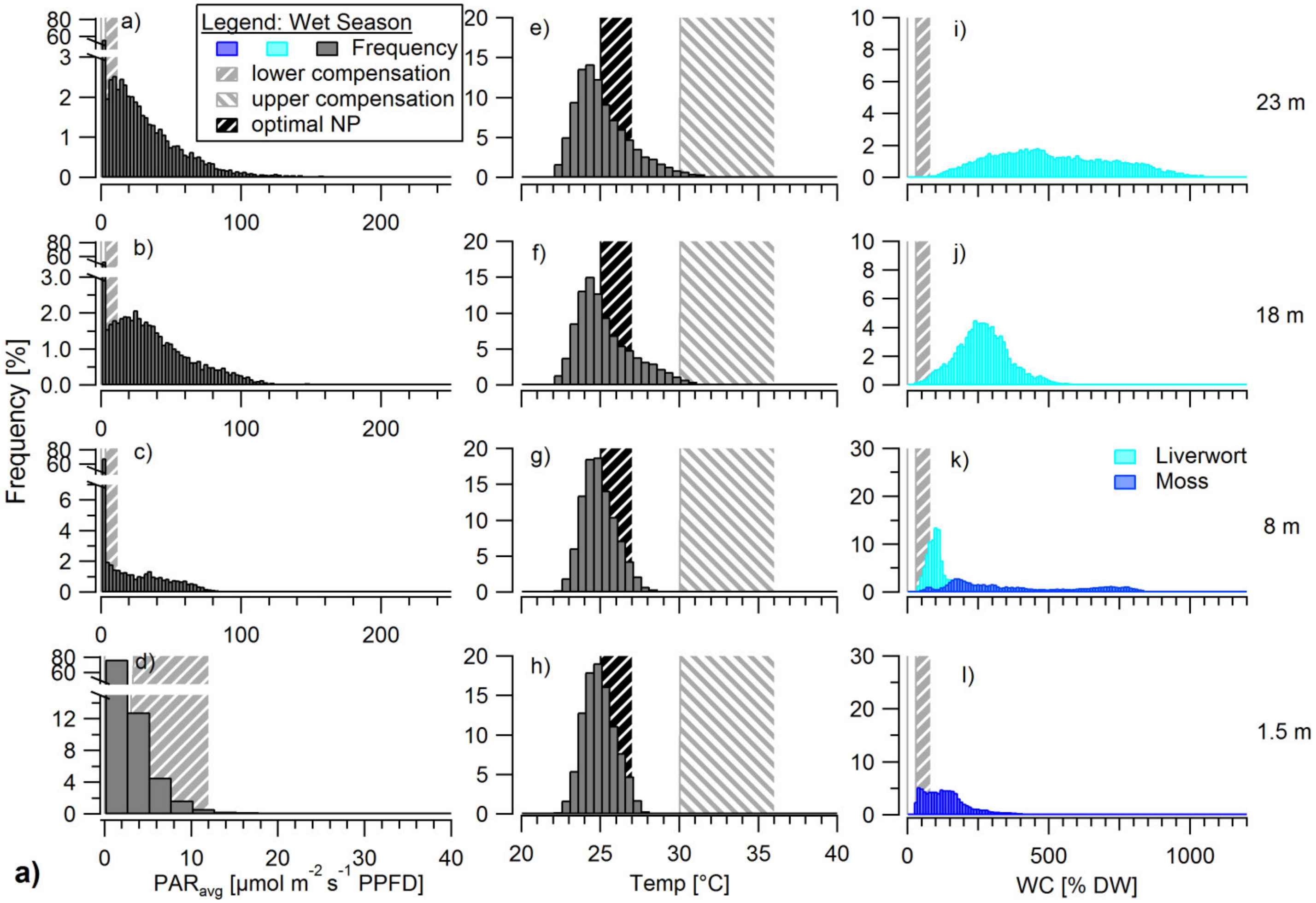
Figure 4:

Previous version with the whole year, and the separation into a) wet and b) dry season.



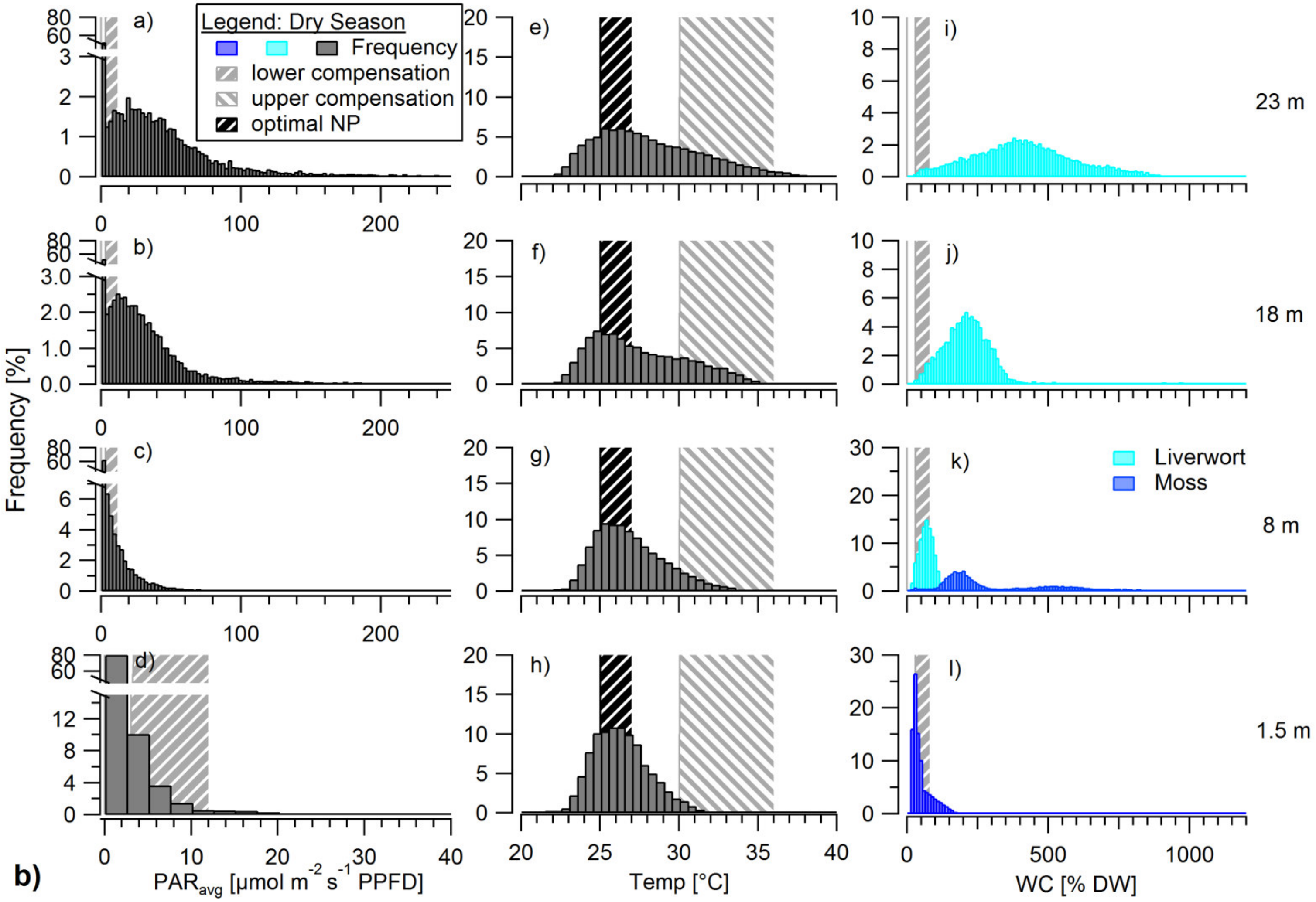
Exemplary results for the percentiles 1 and 99

Physiological activity separated in wet and dry season:



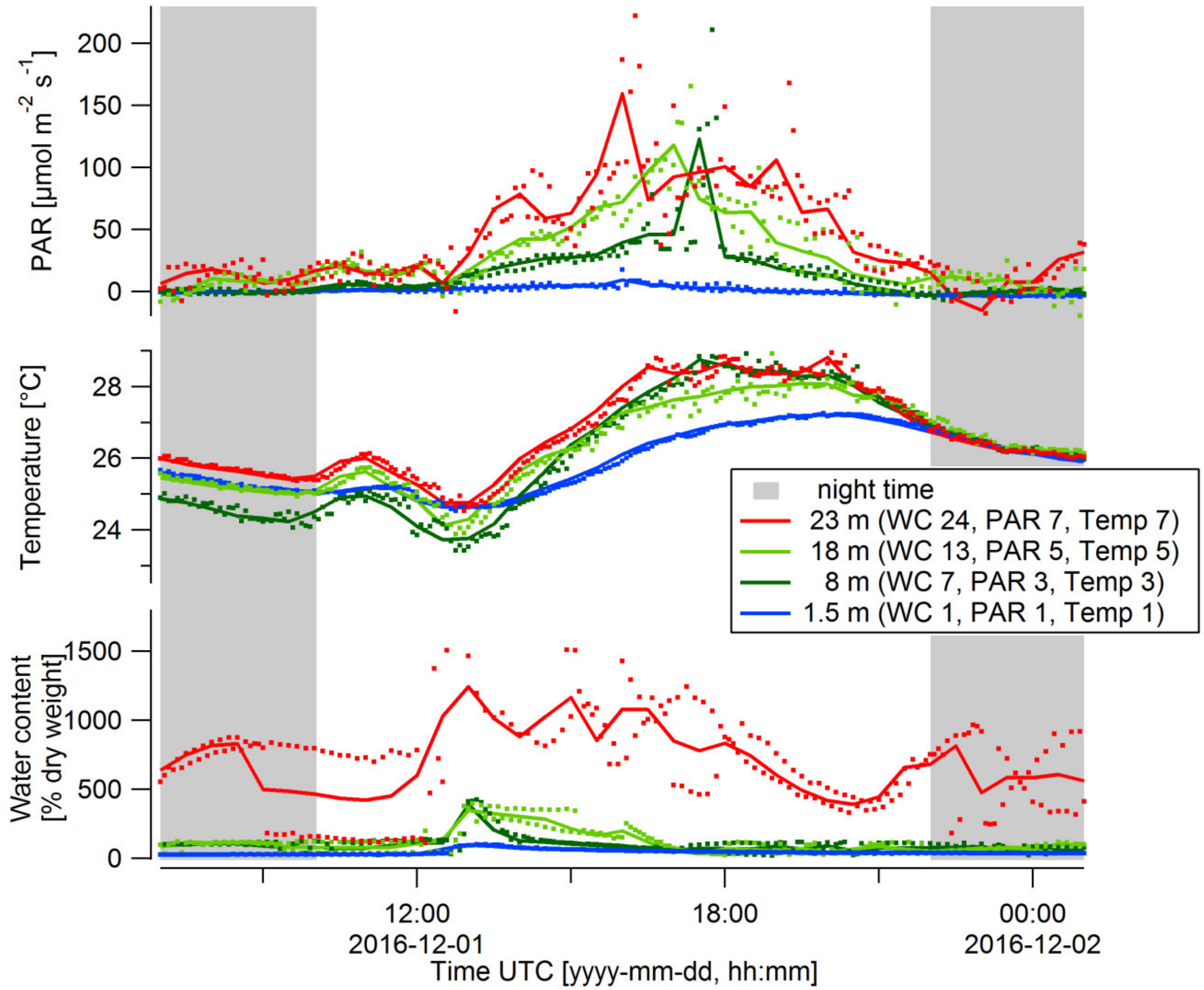
a)

Exemplary results for the percentiles 1 and 99



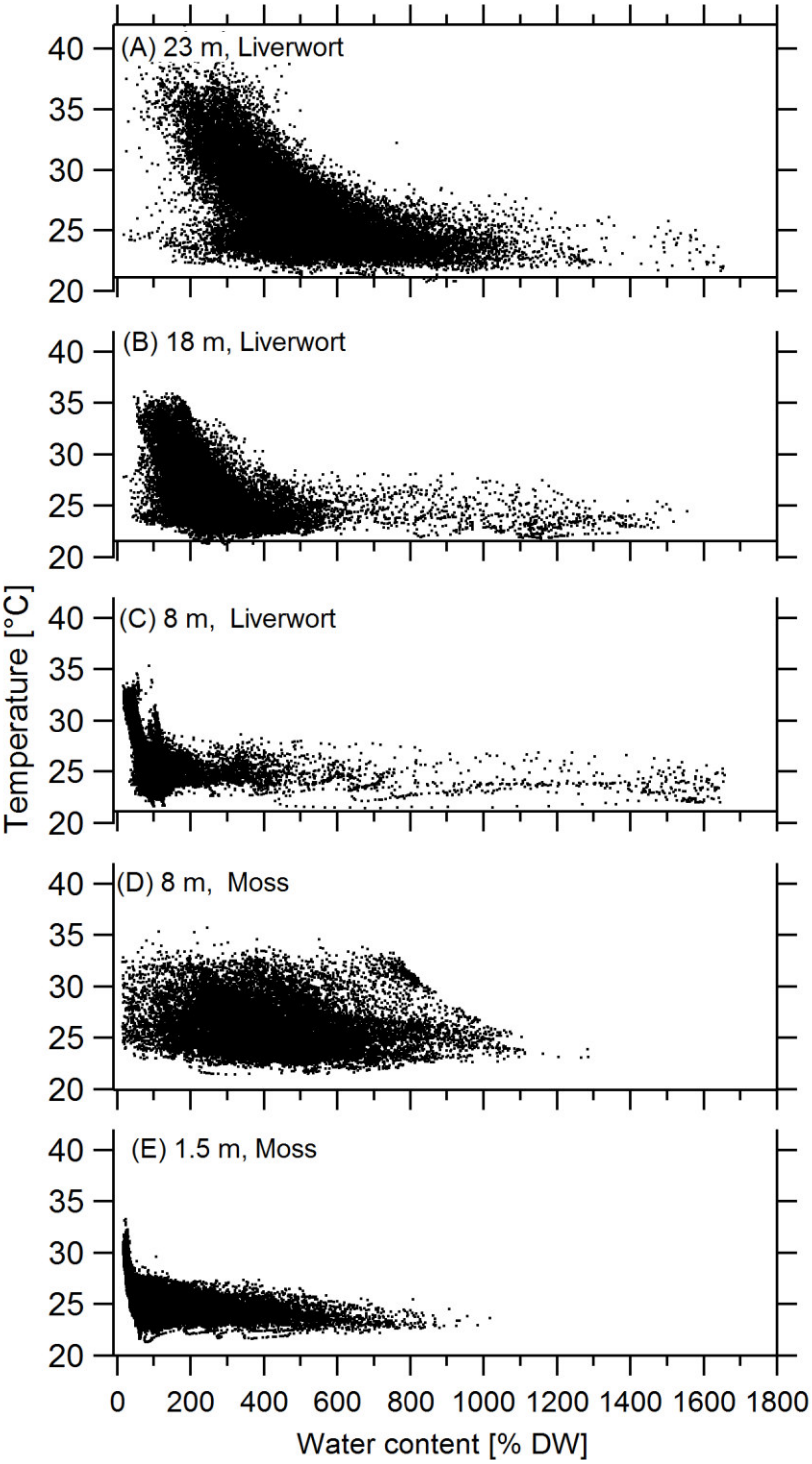
Exemplary results for the percentiles 1 and 99

Figure S5



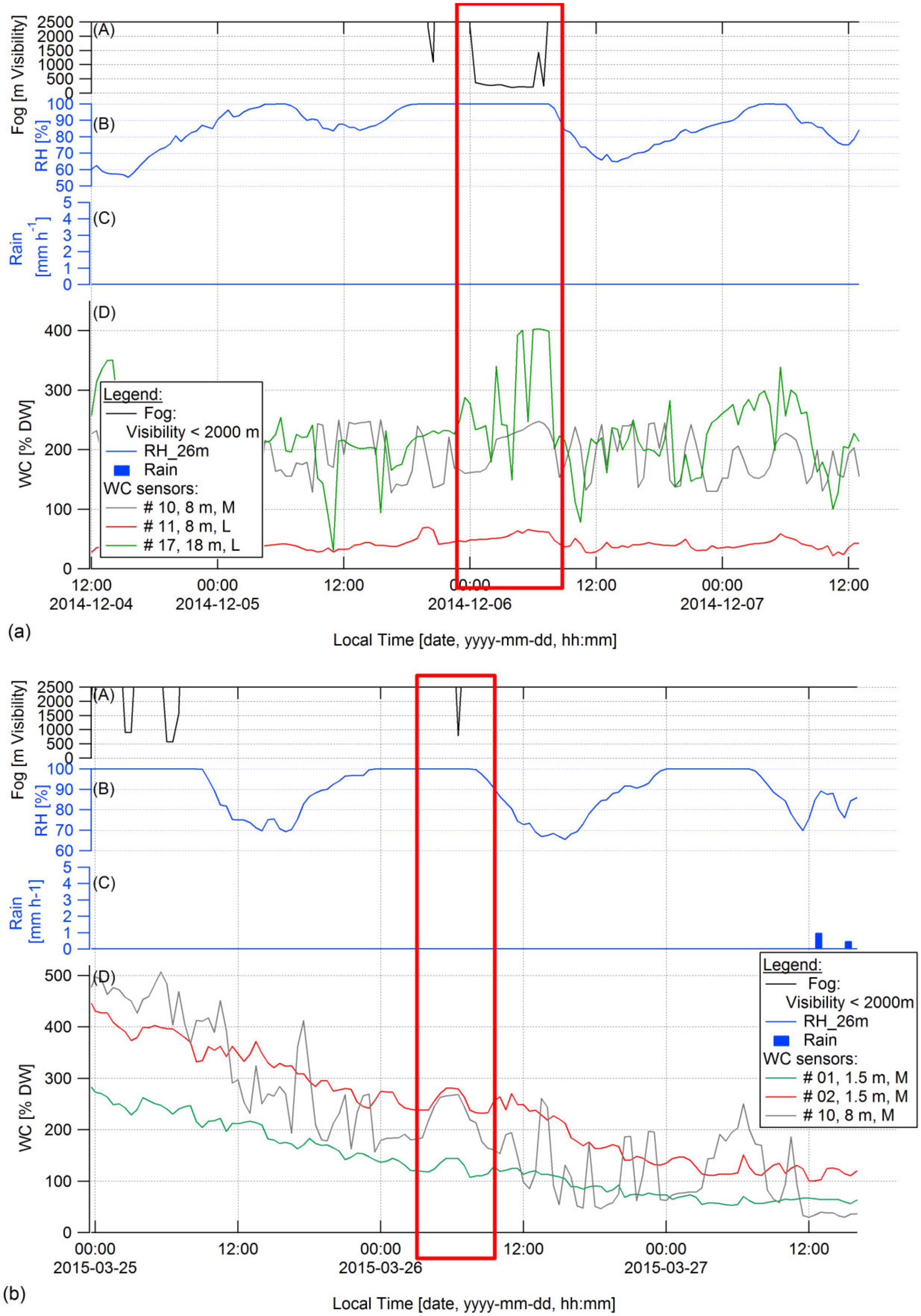
Exemplary results for the percentiles 1 and 99

Figure S10



Exemplary results for the percentiles 1 and 99

Figure S9



Exemplary results for the percentiles 1 and 99

Table 1

Water content [% DW]	2015		2016	
ambient RH, 26	Mean	SD	Mean	SD
23	480	229	526	566
18	246	71	384	426
8L	83	27	196	384
8M	427	278	368	298
1.5	121	56	96	544

Table 2

	mean	sd
Wet		
23	528	179
18	271	101
8L	116	48
8M	409	127
1.5	173	126
Trans Wet-Dry		
23	580	210
18	274	55
8L	84	22
8M	368	139
1.5	79	44
Dry		
23	467	203
18	243	114
8L	93	56
8M	385	148
1.5	71	53
Trans Dry-Wet		
23	491	200
18	294	156
8L	156	105
8M	411	153
1.5	101	83

Table 3

All data

Height	LCPI	Topt	TNP=DR	WCPI	NP		DR	
	3-12 [µmol m-2 s-1 PPFD]	24-27 [°C]	30-36 [°C]	30-80 [% DW]	PAR > LCP		PAR < LCP	
					WC >WCP		T> TCP	
					T<TCP		WC >WCP	
[m]	[% of time]							
23 Liverwort	43-45	6-46	0-16	93-100	22	38	65	60
18 Liverwort	45-48	6-51	0-13	47-100	28	43	49	49
8 Liverwort	37-42	13-29	0-17	6-98	14	39	38	50
8 Moss				81-99	24	40	56	52
1.5 Moss	8-28	14-30	0-11	10-93	1	11	40	65

Wet Season

Height	LCPI	Topt	TNP=DR	WCPI	NP		DR	
	3-12 [µmol m-2 s-1 PPFD]	24-27 [°C]	30-36 [°C]	30-80 [% DW]	PAR > LCP		PAR < LCP	
					WC >WCP		T> TCP	
					T<TCP		WC >WCP	
[m]	[% of time]							
23 Liverwort	34-43	4-54	0-3	88-100	28	38	67	62
18 Liverwort	40-46	4-55	0-2	56-100	33	43	58	57
8 Liverwort	25-31	2-74	0	6-100	22	41	45	57
8 Moss				63-100	30	36	61	63
1.5 Moss	2-19	2-77	0	17-97	1	15	73	81

Dry Season

Height	LCPI	Topt	TNP=DR	WCPI	NP		DR	
	3-12 [µmol m-2 s-1 PPFD]	24-27 [°C]	30-36 [°C]	30-80 [% DW]	PAR > LCP		PAR < LCP	
					WC >WCP		T> TCP	
					T<TCP		WC >WCP	
[m]	[% of time]							
23 Liverwort	42-47	6-34	1-26	80-100	18	40	61	57
18 Liverwort	38-46	5-40	0-23	32-100	21	43	53	54
8 Liverwort	19-36	8-52	0-10	2-92	10	37	44	57
8 Moss				50-99	18	40	62	57
1.5 Moss	4-16	9-60	0-3	1-57	0	10	30	55

Exemplary results for the percentiles 1 and 99

Table S1

				[% DW]	
Species	Type	Height [m]	WC	min	max
Sematophyllum subsimplex	Moss	1.5	Sensor 01	14	763
Sematophyllum subsimplex	Moss	1.5	Sensor 02	13	763
Sematophyllum subsimplex	Moss	1.5	Sensor 03	13	763
Leucobryum martianum	Moss	1.5	Sensor 04	15	1371
Sematophyllum subsimplex	Moss	1.5	Sensor 05	13	761
Sematophyllum subsimplex	Moss	1.5	Sensor 06	16	763
Symbiezidium barbiflorum	Liverwort	8	Sensor 07	16	1658
Octoblepharum cocuiense	Moss	8	Sensor 08	16	1318
Octoblepharum cocuiense	Moss	8	Sensor 09	15	1316
Octoblepharum cocuiense	Moss	8	Sensor 10	15	1309
Symbiezidium barbiflorum	Liverwort	8	Sensor 11	16	1658
Symbiezidium barbiflorum	Liverwort	8	Sensor 12	16	1653
Symbiezidium barbiflorum	Liverwort	18	Sensor 13	16	1647
Symbiezidium barbiflorum	Liverwort	18	Sensor 14	16	1645
Symbiezidium barbiflorum	Liverwort	18	Sensor 15	17	1656
Symbiezidium barbiflorum	Liverwort	18	Sensor 16	17	1658
Symbiezidium barbiflorum	Liverwort	18	Sensor 17	16	1658
Symbiezidium barbiflorum	Liverwort	18	Sensor 18	16	1633
Symbiezidium barbiflorum	Liverwort	23	Sensor 19	17	1656
Symbiezidium barbiflorum	Liverwort	23	Sensor 20		
Symbiezidium barbiflorum	Liverwort	23	Sensor 21	17	1654
Symbiezidium barbiflorum	Liverwort	23	Sensor 22	17	1652
Symbiezidium barbiflorum	Liverwort	23	Sensor 23	17	1656
Symbiezidium barbiflorum	Liverwort	23	Sensor 24	16	1657

Exemplary results for the percentiles 1 and 99

Table S4

updated										
	Water content [% DW]									
Month	**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**
Oct-14	243	188	449	185	97	32	262	149	632	279
Nov-14	77	52	346	64	90	14	241	151	537	245
Dec-14	96	92	363	78	89	17	248	144	435	157
Jan-15	217	172	438	105	99	20	255	136	492	182
Feb-15	178	138	417	99	97	15	236	84	537	163
Mar-15	226	147	480	136	116	21	314	126	565	139
Apr-15	147	108	387	77	100	18	310	137	555	164
May-15	232	165	530	117	96	17	264	102	547	169
Jun-15							273	50	574	173
Jul-15	89	54	360	109	84	22	275	61	536	202
Aug-15	58	25	343	95	70	20	237	73	464	172
Sep-15	39	38	300	93	61	20	196	66	340	158
Oct-15	39	30	524	205	61	20	198	71	389	189
Nov-15	45	32	502	206	67	40	202	64	421	193
Dec-15	41	24	478	201	65	32	201	64	414	184
Jan-16	44	31	303	127	63	36	195	70	431	188
Feb-16	170	151	359	159	118	80	249	78	514	205
Mar-16	172	129	335	138	130	70	253	82	513	188
Apr-16	156	103	412	153	174	104			524	227
May-16	105	67	354	141	94	61			471	180
Jun-16	81	40	359	145					595	212
Jul-16	67	39	386	164					613	252
Aug-16	51	54	323	144					498	199
Sep-16	55	51	361	174						
Oct-16	42	16								
Nov-16	59	45	319	166	205	248	368	227	456	193
Dec-16	109	94	475	253	463	418	570	368	683	286

Exemplary results for the percentiles 1 and 99

Exemplary results for the percentiles 5 and 95

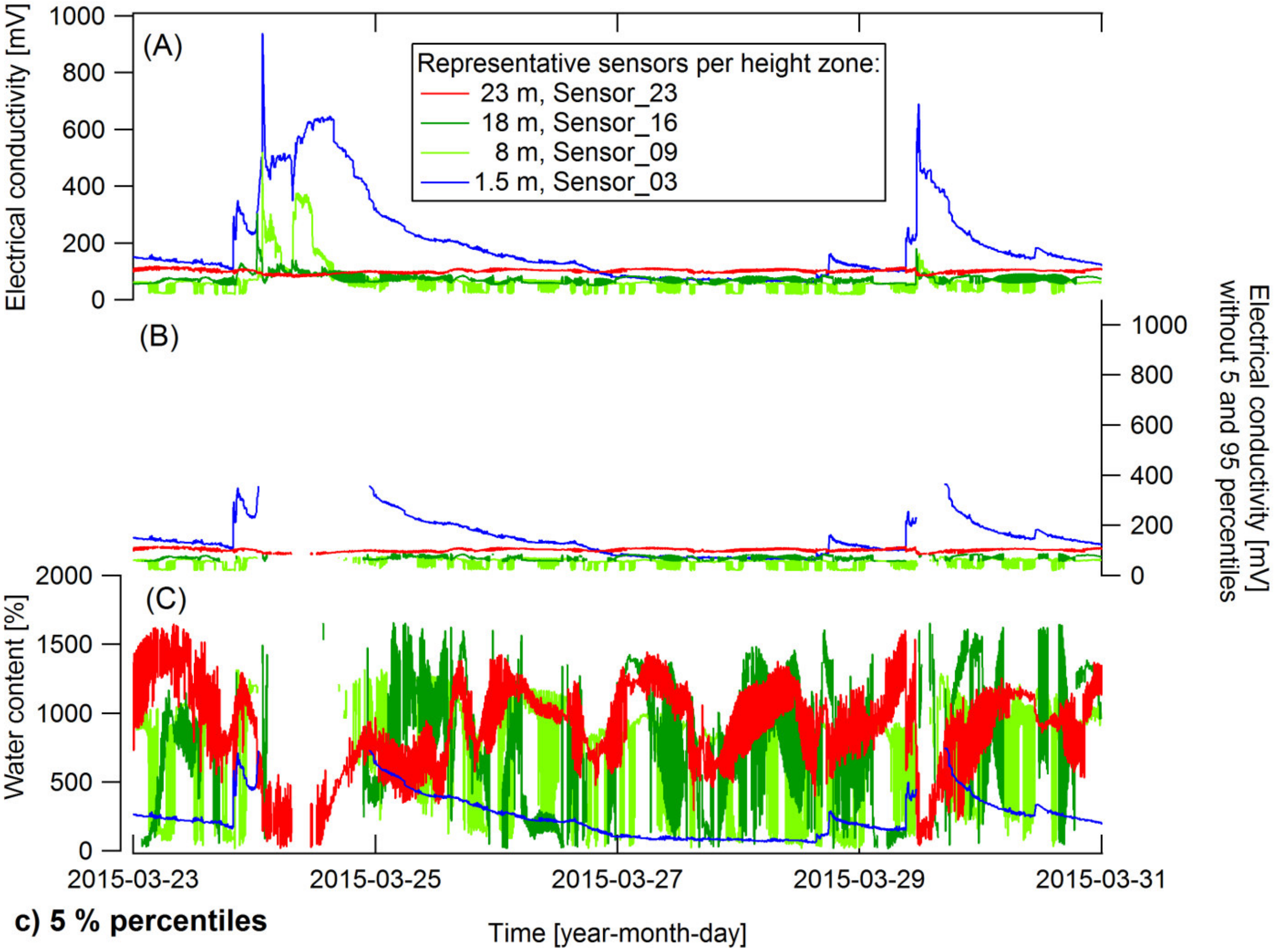
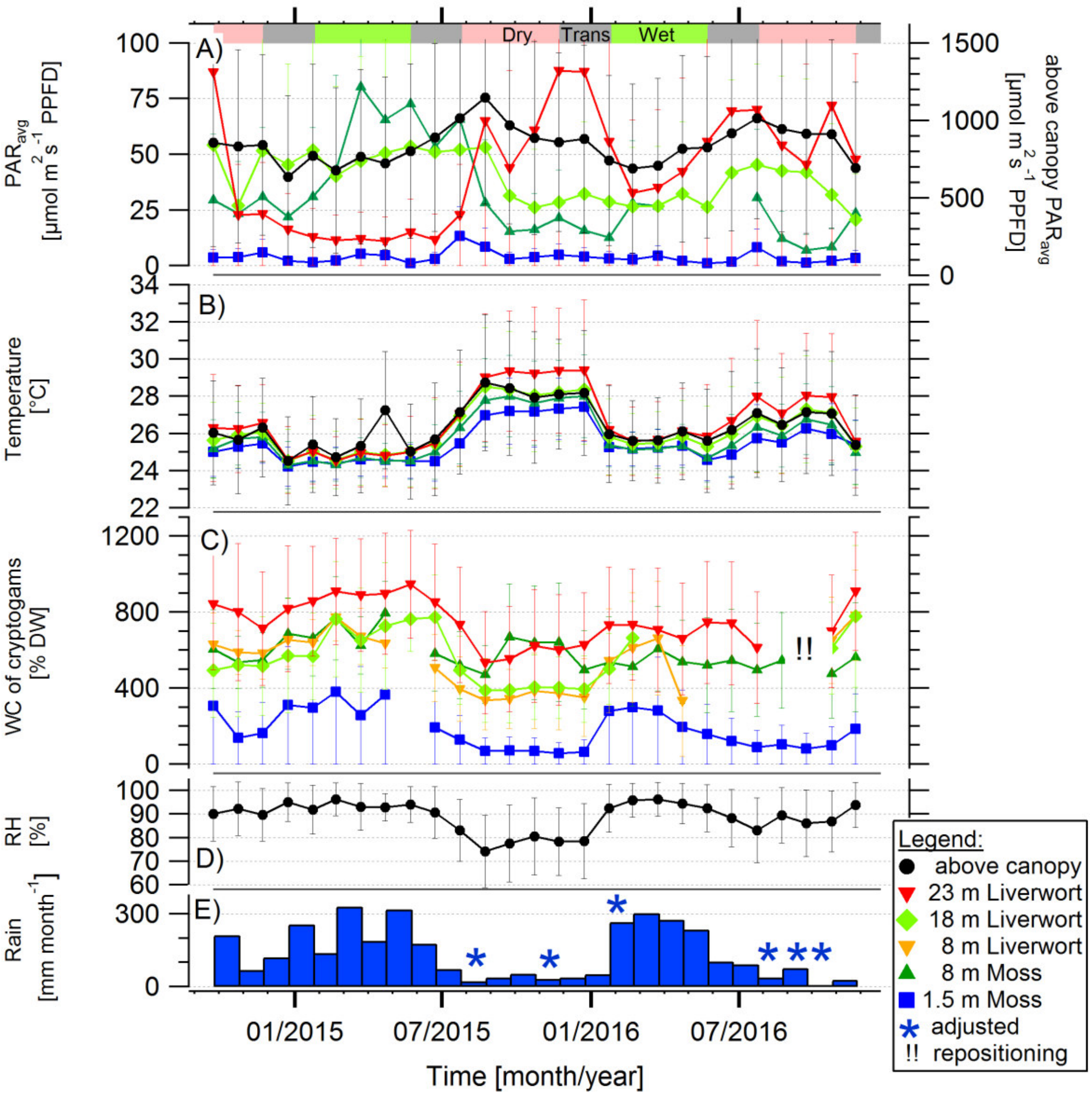


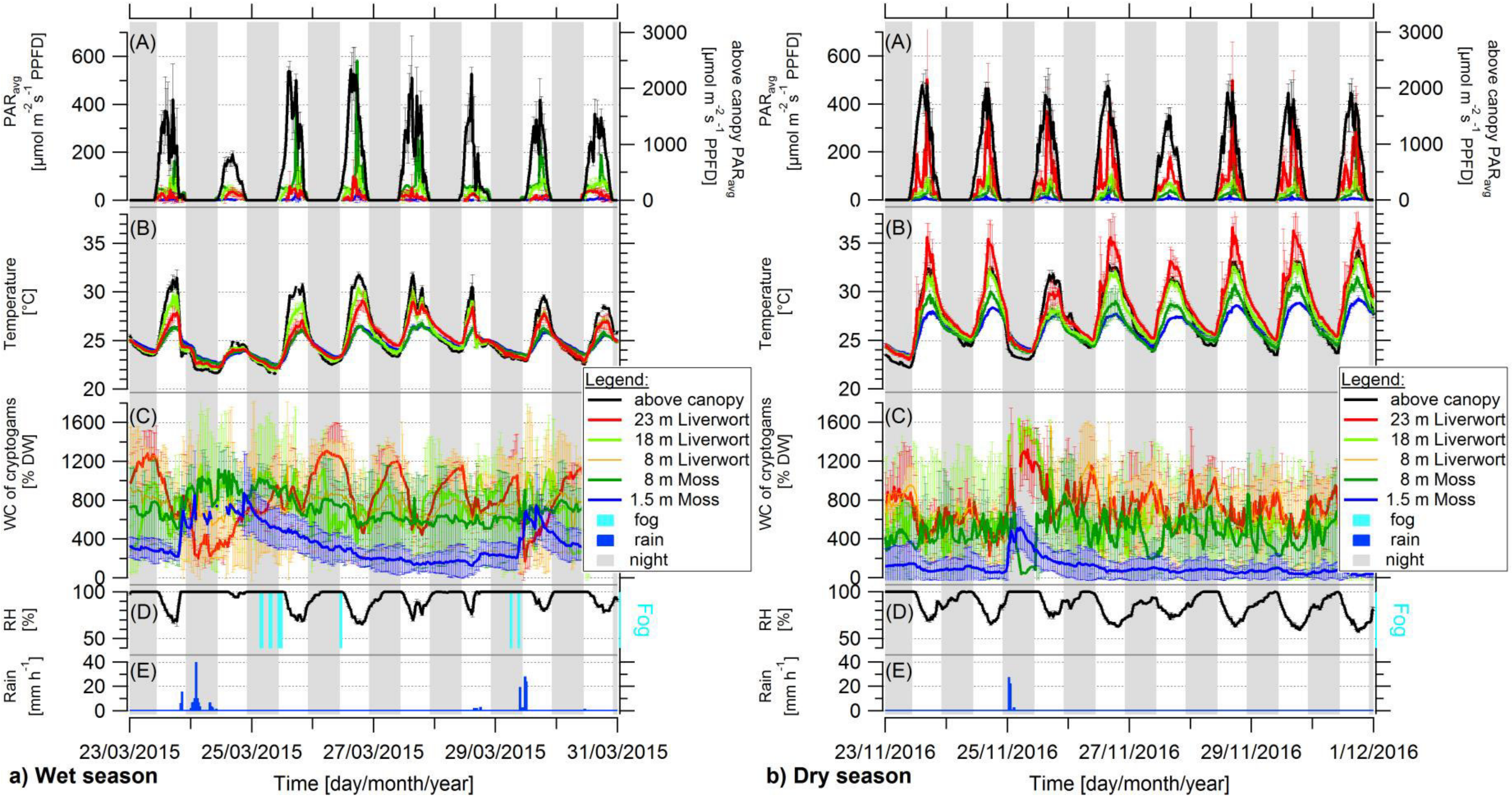
Figure S7 c): Exemplary snapshots of the conversion from (A) the measured electrical conductivity, via (B) the electrical conductivity minus the upper and the lower percentiles, to (C) the water content of the epiphytic bryophytes. The figure shows c) the 5 % percentiles (from Figure S7 of the Manuscript). The same time frame as in Figure 2a) was chosen. Data shown as 5 minute intervals.

Figure 1



Exemplary results for the percentiles 5 and 95

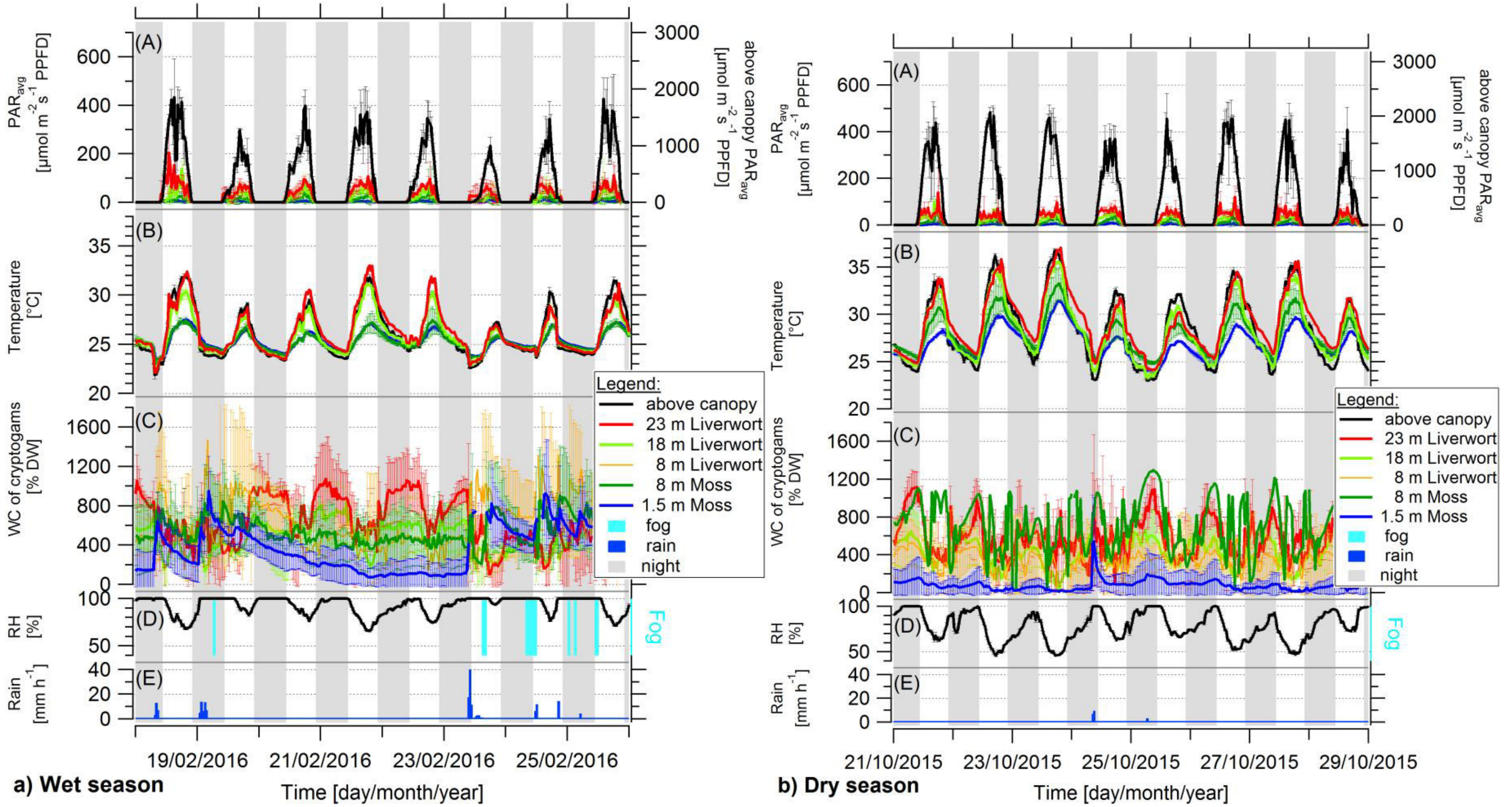
Fig 2"Normal Year":



a) Wet season

b) Dry season

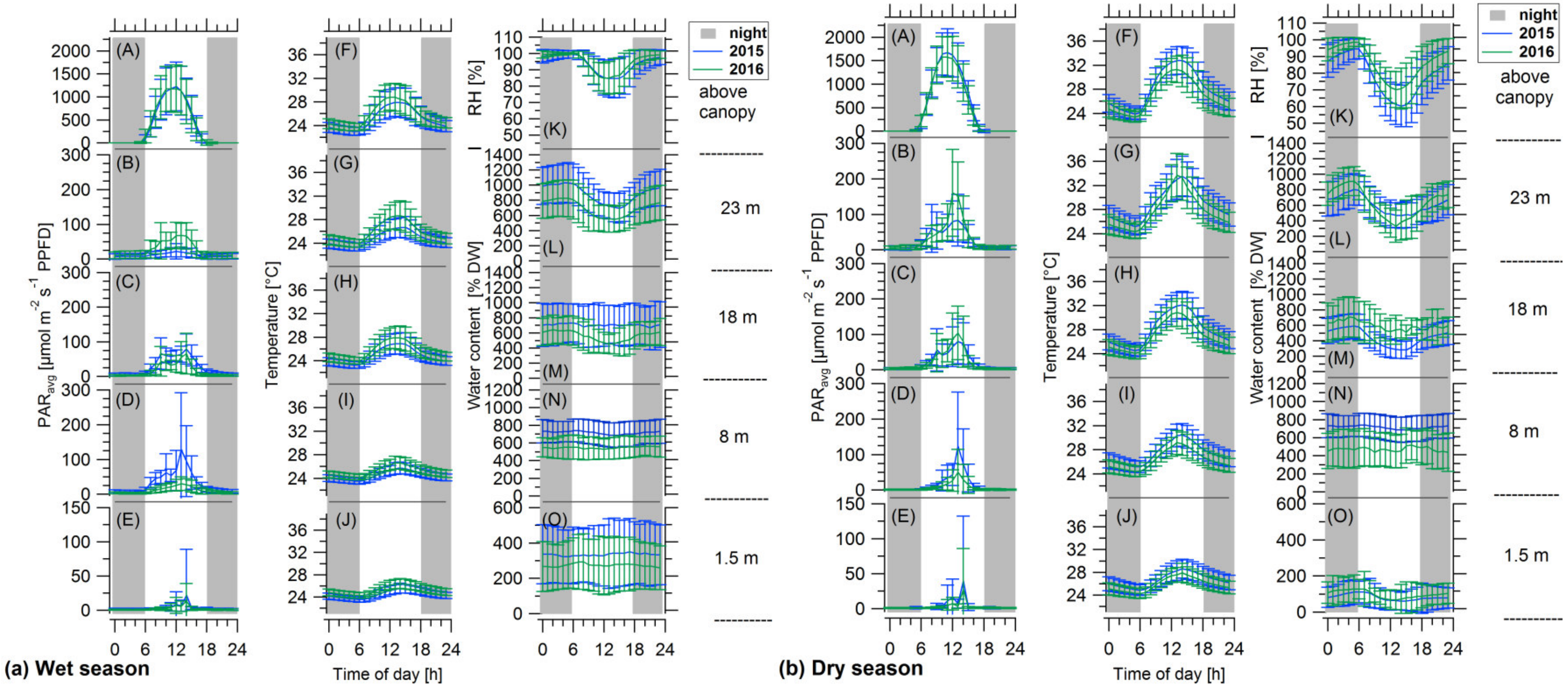
Fig. s6 “El Nino Year”



a) Wet season

b) Dry season

Figure 3



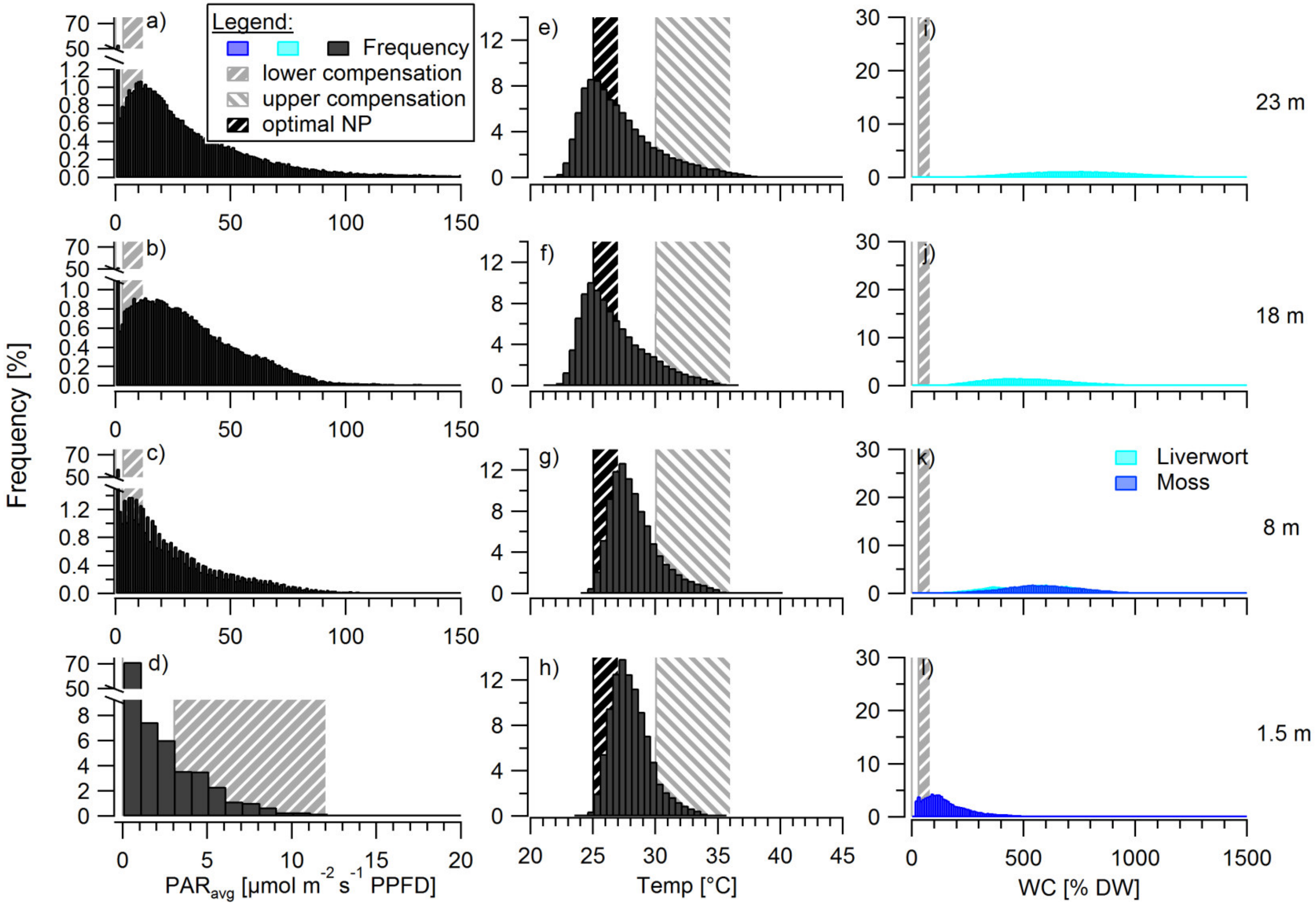
(a) Wet season

(b) Dry season

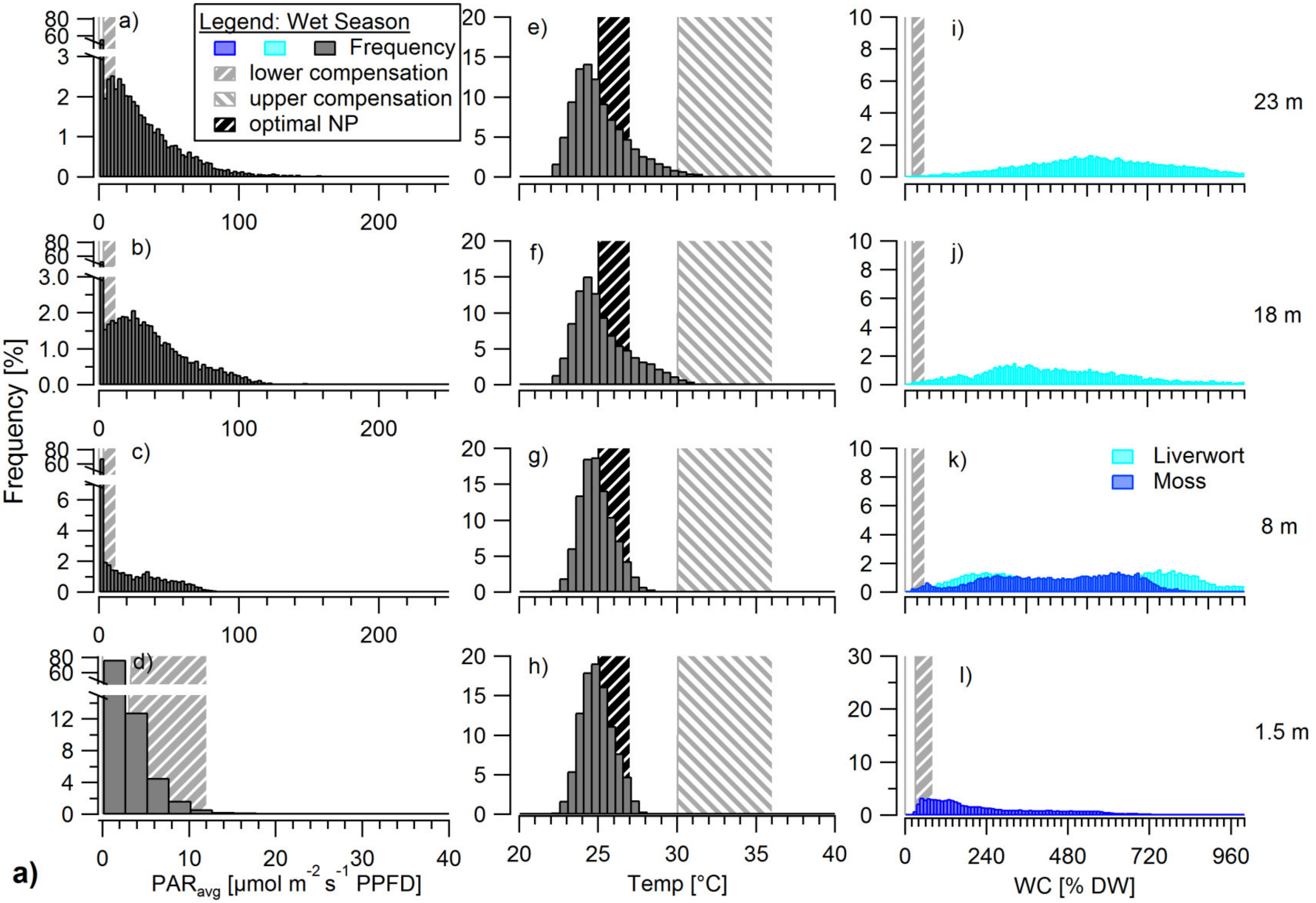
Exemplary results for the percentiles 5 and 95

Figure 4:

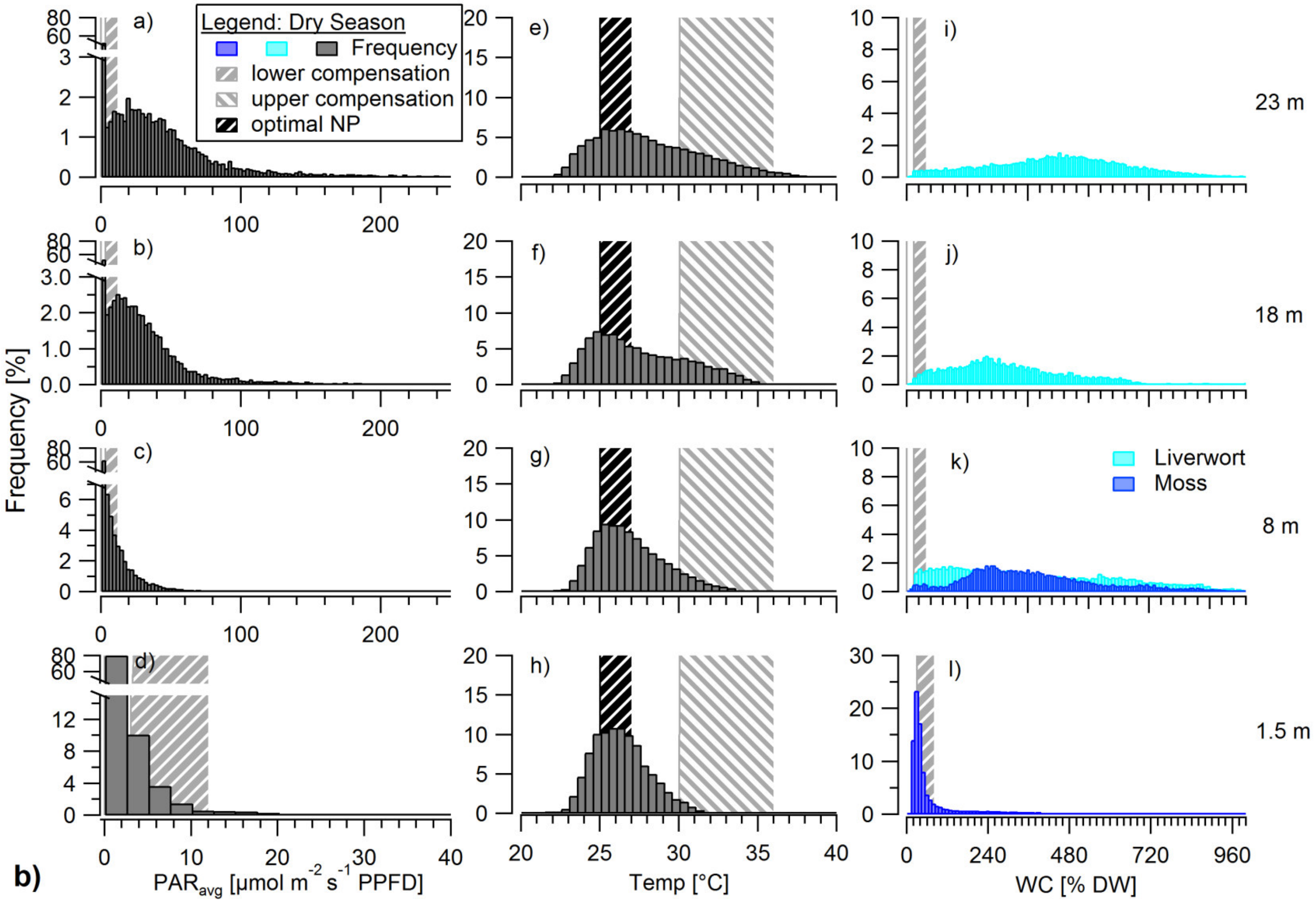
Previous version with the whole year, and the separation into a) wet and b) dry season.



Physiological activity separated in wet and dry season:



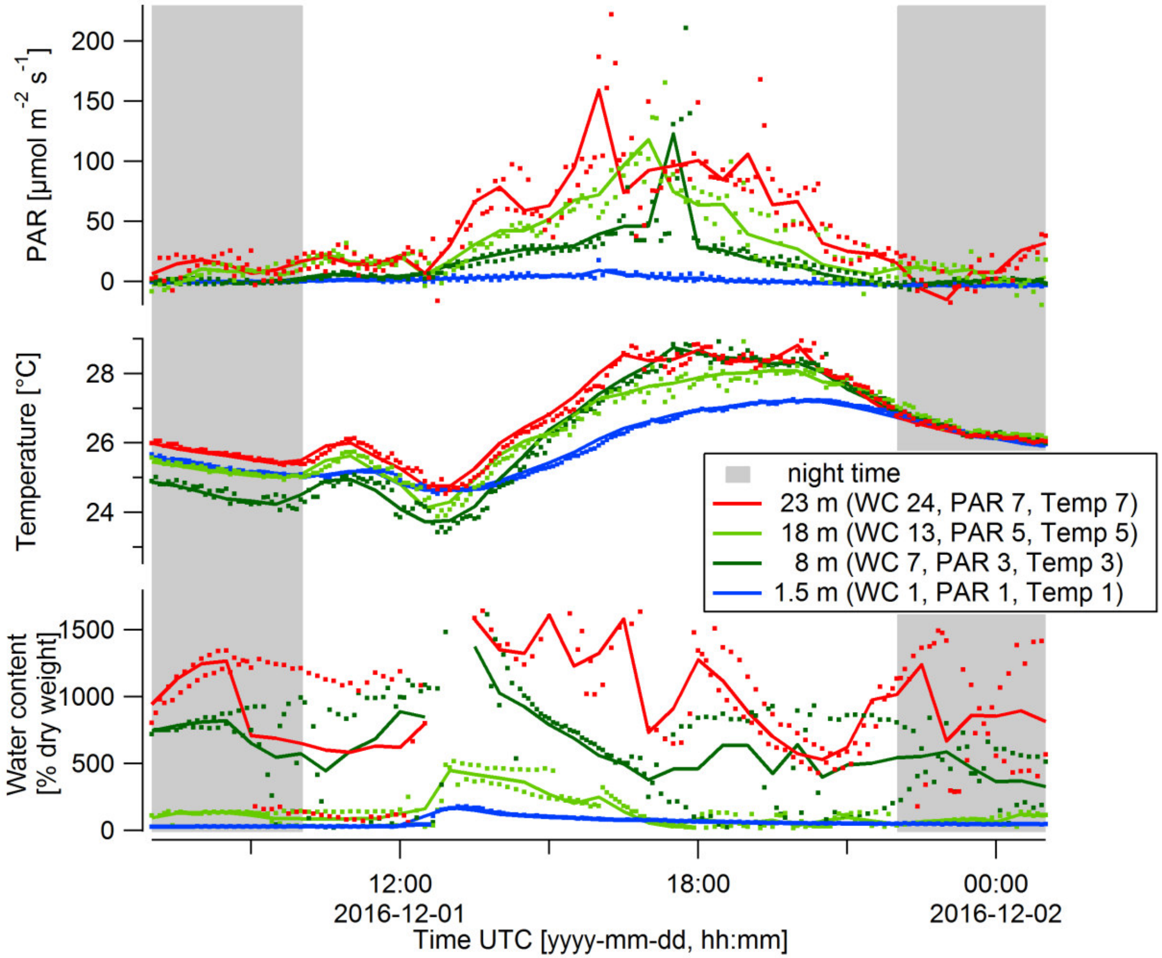
Exemplary results for the percentiles 5 and 95



b)

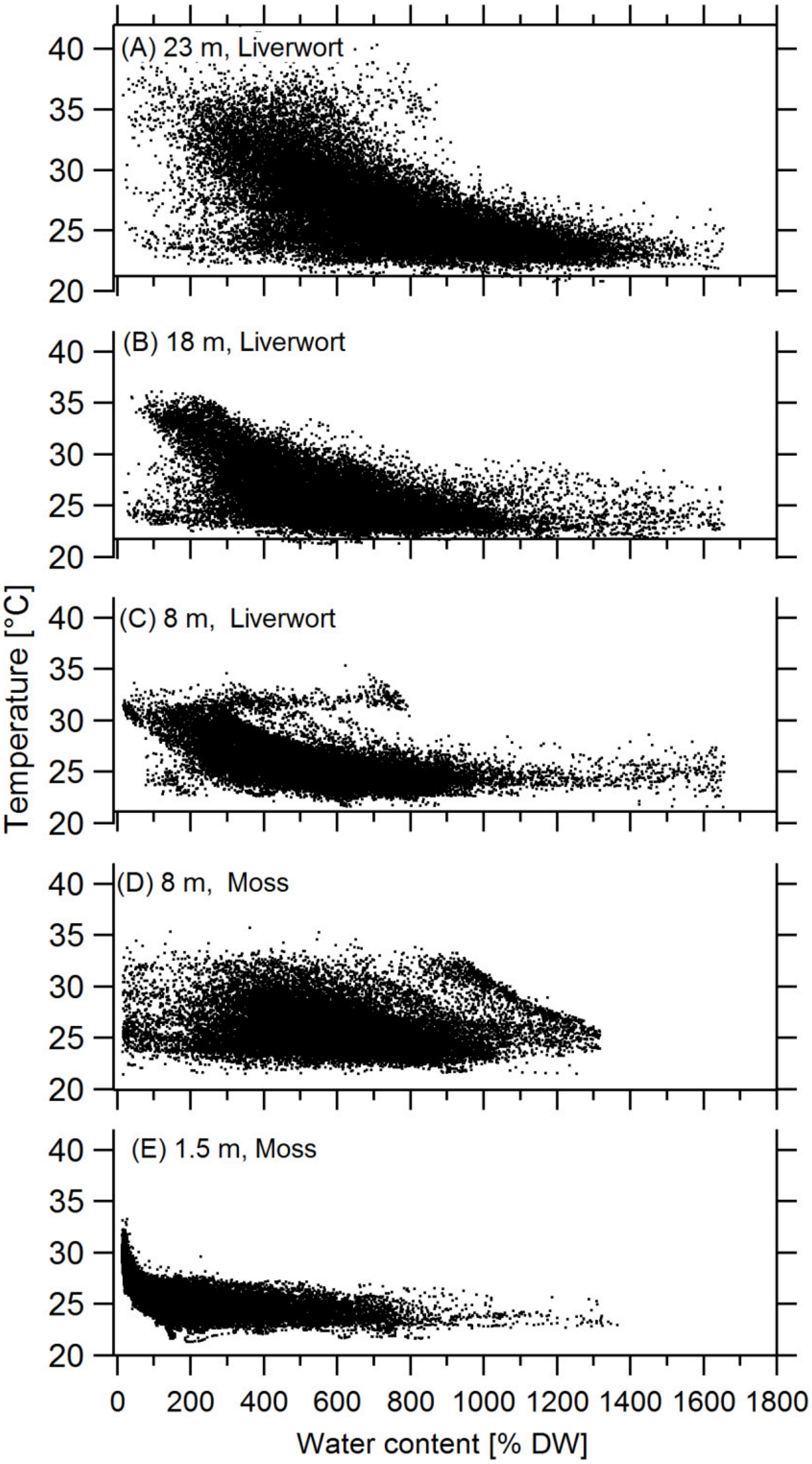
Exemplary results for the percentiles 5 and 95

Figure S5



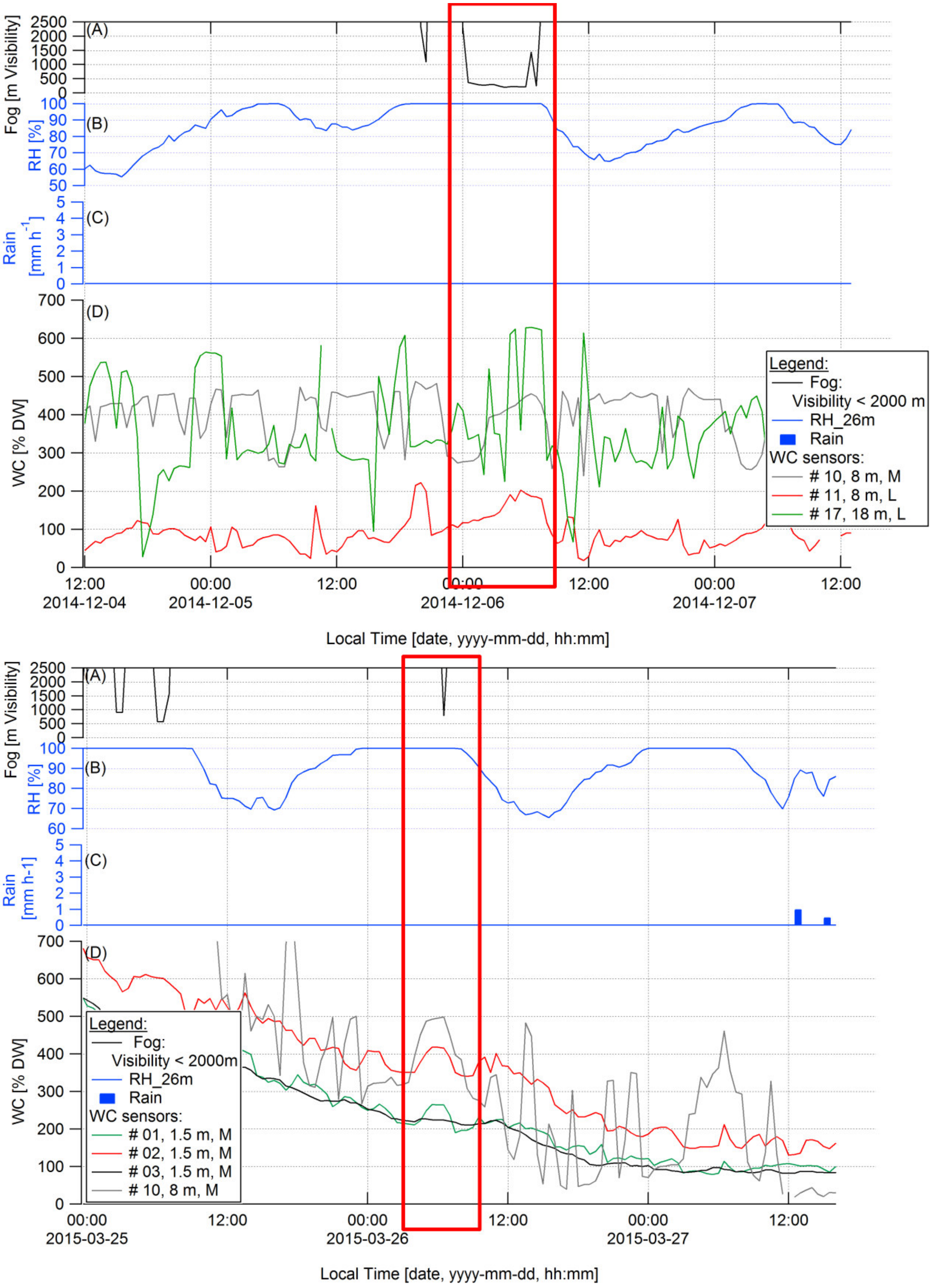
Exemplary results for the percentiles 5 and 95

Figure S10



Exemplary results for the percentiles 5 and 95

Figure S9



Exemplary results for the percentiles 5 and 95

Table 1

	2015		2016	
	Mean	SD	Mean	SD
23L	430	136	469	180
18L	215	73	305	252
8L	65	19	170	248
8M	368	123	306	131
1.5M	111	119	83	78

Table 2

	mean	sd
Wet		
23	453	145
18	234	84
8L	87	34
8M	336	104
1.5	153	115
Trans Wet-Dry		
23	518	185
18	234	44
8L	66	16
8M	303	110
1.5	70	38
Dry		
23	411	183
18	217	104
8L	76	52
8M	320	125
1.5	64	47
Trans Dry-Wet		
23	433	177
18	264	143
8L	134	97
8M	343	128
1.5	92	76

Exemplary results for the percentiles 5 and 95

Table 3

All data					Worst to Best Case Scenario				
						[% of time]		[% of time]	
	[% of tim	% of time	[% of time]	[% of time]	Conditions	**NP**		**DR**	
Height	**LCPI**	**Topt**	**TNP=DR**	**WCPI**	for NP and DR	PAR > LCP		PAR < LCP	
	3-12	24-27	30-36	30-80		WC >WCP		T> TCP	
[m]	[µmol m-2 s-1 PPFD]	[°C]	[°C]	[% DW]	PAR/T/WC	T<TCP		WC >WCP	
23 Liverwort	43-45	6-46	0-16	96-100	3-12/30-36/30-80	21	38	65	61
18 Liverwort	45-48	6-51	0-13	91-100	3-12/30-36/30-80	29	43	50	49
8 Liverwort	37-42	13-29	0-17	90-100	3-12/30-36/30-80	24	41	60	52
8 Moss				91-99	3-12/30-36/30-80	25	40	58	52
1.5 Moss	8-28	14-30	0-11	24-93	3-12/30-36/30-80	1	11	48	69

Wet Season					Worst to Best Case Scenario				
						[% of time]		[% of time]	
	[% of tim	% of time	[% of time]	[% of time]	Conditions	**NP**		**DR**	
Height	**LCPI**	**Topt**	**TNP=DR**	**WCPI**	for NP and DR	PAR > LCP		PAR < LCP	
	3-12	24-27	30-36	30-80		WC >WCP		T> TCP	
[m]	[µmol m-2 s-1 PPFD]	[°C]	[°C]	[% DW]	PAR/T/WC	T<TCP		WC >WCP	
23 Liverwort	34-43	4-54	0-3	95-100	3-12/30-36/30-80	28	38	67	62
18 Liverwort	40-46	4-55	0-2	89-100	3-12/30-36/30-80	34	42	59	57
8 Liverwort	25-31	2-74	0	81-100	3-12/30-36/30-80	34	42	63	57
8 Moss				90-100	3-12/30-36/30-80	31	37	64	63
1.5 Moss	2-19	2-77	0	45-99	3-12/30-36/30-80	1	15	83	83

Dry Season					Worst to Best Case Scenario				
						[% of time]		[% of time]	
	[% of tim	% of time	[% of time]	[% of time]	Conditions	**NP**		**DR**	
Height	**LCPI**	**Topt**	**TNP=DR**	**WCPI**	for NP and DR	PAR > LCP		PAR < LCP	
	3-12	24-27	30-36	30-80		WC >WCP		T> TCP	
[m]	[µmol m-2 s-1 PPFD]	[°C]	[°C]	[% DW]	PAR/T/WC	T<TCP		WC >WCP	
23 Liverwort	42-47	6-34	1-26	87-99	3-12/30-36/30-80	17	39	61	58
18 Liverwort	38-46	5-40	0-23	75-99	3-12/30-36/30-80	23	44	54	54
8 Liverwort	19-36	8-42	0-10	63-98	3-12/30-36/30-80	19	39	71	60
8 Moss				86-99	3-12/30-36/30-80	19	40	67	58
1.5 Moss	4-16	9-60	0-3	13-63	3-12/30-36/30-80	1	10	36	59

Exemplary results for the percentiles 5 and 95

Table S1

				[% DW]	
Species	Type	Height [m]	WC	min	max
Sematophyllum subsimplex	Moss	1.5	Sensor 01	13	760
Sematophyllum subsimplex	Moss	1.5	Sensor 02	13	763
Sematophyllum subsimplex	Moss	1.5	Sensor 03	13	763
Leucobryum martianum	Moss	1.5	Sensor 04	15	1367
Sematophyllum subsimplex	Moss	1.5	Sensor 05	13	763
Sematophyllum subsimplex	Moss	1.5	Sensor 06	14	763
Symbiezidium barbiflorum	Liverwort	8	Sensor 07	16	1658
Octoblepharum cocuiense	Moss	8	Sensor 08	16	1315
Octoblepharum cocuiense	Moss	8	Sensor 09	15	1316
Octoblepharum cocuiense	Moss	8	Sensor 10	15	1308
Symbiezidium barbiflorum	Liverwort	8	Sensor 11	16	1655
Symbiezidium barbiflorum	Liverwort	8	Sensor 12	16	1658
Symbiezidium barbiflorum	Liverwort	18	Sensor 13	17	1658
Symbiezidium barbiflorum	Liverwort	18	Sensor 14	17	1656
Symbiezidium barbiflorum	Liverwort	18	Sensor 15	17	1637
Symbiezidium barbiflorum	Liverwort	18	Sensor 16	16	1658
Symbiezidium barbiflorum	Liverwort	18	Sensor 17	16	1652
Symbiezidium barbiflorum	Liverwort	18	Sensor 18	16	1653
Symbiezidium barbiflorum	Liverwort	23	Sensor 19	16	1641
Symbiezidium barbiflorum	Liverwort	23	Sensor 20		
Symbiezidium barbiflorum	Liverwort	23	Sensor 21	17	1645
Symbiezidium barbiflorum	Liverwort	23	Sensor 22	17	1631
Symbiezidium barbiflorum	Liverwort	23	Sensor 23	16	1657
Symbiezidium barbiflorum	Liverwort	23	Sensor 24	17	1647

Exemplary results for the percentiles 5 and 95

Table S4

	Water content [% DW]									
Month	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
Oct-14	225	177	386	176	75	25	232	132	540	263
Nov-14	69	45	285	50	70	10	213	138	495	242
Dec-14	87	87	298	61	70	12	220	131	394	134
Jan-15	193	161	358	81	77	14	220	113	446	169
Feb-15	158	124	342	77	75	11	203	69	482	143
Mar-15	197	128	391	112	89	15	264	102	506	117
Apr-15	132	102	318	60	77	13	271	117	486	133
May-15	204	151	440	101	75	12	225	82	478	137
Jun-15							233	40	500	138
Jul-15	76	45	293	84	66	16	235	49	458	179
Aug-15	50	21	283	76	56	14	210	62	395	141
Sep-15	36	35	245	75	49	14	176	56	298	153
Oct-15	36	25	429	169	49	14	176	61	343	172
Nov-15	42	28	418	169	54	28	180	54	362	161
Dec-15	39	20	398	165	52	23	179	54	357	157
Jan-16	42	28	249	101	51	25	174	59	371	166
Feb-16	154	141	296	131	90	59	222	66	443	175
Mar-16	154	122	276	113	96	47	217	65	413	145
Apr-16	136	88	338	127	127	74			426	171
May-16	93	62	290	110	71	42			389	137
Jun-16	72	35	293	114					543	181
Jul-16	60	34	322	133					570	241
Aug-16	45	44	270	122					459	174
Sep-16	49	45	300	141						
Oct-16	37	14								
Nov-16	54	40	268	148	179	258	329	226	394	160
Dec-16	98	85	413	229	419	412	528	356	597	258