



DATA PAPER  

High-resolution tropical rain-forest canopy climate data

Monica B. Berdugo^{1,*} , Leander Heyer¹, Karen Yuliana Suarez Contento², Jorge Déleg³, Jörg Bendix⁴  and Maaïke Y. Bader¹

¹Ecological Plant Geography, Faculty of Geography, University of Marburg, Marburg, Germany

²Plant Taxonomy Laboratory, Department of Biology, Federal Rural University of Pernambuco, Recife, Brazil

³Herbario HUTPL, Departamento de Ciencias Naturales, Universidad Técnica Particular de Loja, Loja, Ecuador

⁴Laboratory for Climatology and Remote Sensing, Faculty of Geography, University of Marburg, Marburg, Germany

*Corresponding author. E-mail: biobibiana@yahoo.com

Received: 03 May 2022; **Revised:** 11 August 2022; **Accepted:** 06 September 2022



Keywords: Amazon forest; canopy climate; Ecuador; tree crowns; Yasuní National Park

Abstract

Canopy habitats challenge researchers with their intrinsically difficult access. The current scarcity of climatic data from forest canopies limits our understanding of the conditions and environmental variability of these diverse and dynamic habitats. We present 307 days of climate records collected between 2019 and 2020 in the tropical rainforest canopy of the Yasuní National Park, Ecuador. We monitored climate with a 10-min temporal resolution in the middle crowns of eight canopy trees. The distance between canopy climate stations ranged from 700 m to 10 km. Apart from air temperature, relative humidity, leaf wetness, and photosynthetically active radiation (PAR), measured in each canopy climate station, global radiation, rainfall, and wind speed were measured in different subsets of them. We processed the eight data series to omit erroneous records resulting from sensor failures or lack of the solar-based power supply. In addition to the eight original data series, we present three derived data series, two aggregating canopy climate for valleys or for ridges (from four stations each), and one overall average (from the eight stations). This last derived data series contains 306 days, while the shortest of the original data series covers 22 days and the longest 296 days. In addition to the data, two open-source tools, developed in RStudio, are presented that facilitate data visualization (a dashboard) and data exploration (a filtering app) of the original and aggregated records.

Impact Statement

Climate data from tropical forest canopies are scarce, yet crucial to understanding tropical canopy dynamics. We encourage the use of our high-resolution climate data series as a field-based reference to validate models simulating the microclimate of these canopies. Furthermore, these data series can be used as climate inputs to model small-scale and fast-paced ecological dynamics driven by climate, such as the photosynthesis of canopy-dwelling organisms.

  This research article was awarded Open Data and Open Materials badges for transparent practices. See the Data Availability Statement for details.

© The Author(s), 2022. Published by Cambridge University Press. This is an Open Access article, distributed under the terms of the Creative Commons Attribution licence (<http://creativecommons.org/licenses/by/4.0>), which permits unrestricted re-use, distribution and reproduction, provided the original article is properly cited.

1. Introduction

Forest canopy climate is important for the performance of trees (Luo, 2007; O'Grady et al., 2011) as well as for sessile and mobile organisms living in the dynamic canopy habitat (Suggitt et al., 2017). Forest canopies host a wealth of biological diversity (Barker and Pinard, 2001) and canopy climate factors such as temperature, relative humidity, and light intensity drive and constrain the physiological performance, ecology, and fitness of sporadic and permanent inhabitants (Suggitt et al., 2017). In addition to hosting sessile organisms, such as plants and lichens (i.e., epiphytes), canopies host mobile organisms ranging in size from microorganisms and arthropods to all groups of vertebrates (Nakamura et al., 2017). This astonishing diversity is a common descriptor for canopies in mature tropical forests, yet canopy climate records describing the conditions met by these diverse organisms are particularly scarce, despite the expansion of canopy research at tropical latitudes in recent decades (Nakamura et al., 2017). Here, we present >300 days of canopy climate records with high temporal resolution (each 10 min) obtained in the lowland tropical forest surrounding the Yasuni scientific station in Amazonian Ecuador, an iconic biodiversity hotspot (Bass et al., 2010).

The intrinsic difficulty to access forest canopies challenges us while studying canopy climate in forests around the world. Yet, the relevance of canopies for biodiversity maintenance calls for persistence, creativity, and cooperation (Barker and Pinard, 2001). In addition, forest canopies contribute importantly to vegetation-climate feedback (Lin et al., 2010; O'Grady et al., 2011). The exchange of relevant gases between canopies and the atmosphere can be highly dynamic, in dependence of climatic fluctuations above and inside the canopy (Luo, 2007; Lin et al., 2010). However, high-temporal-resolution field measurements of canopy climate remain scarce and scattered, limiting our ability to understand such dynamics (Nakamura et al., 2017). This shortage is especially pronounced in tropical forests. Although a modeling approach can supply estimates for the canopy climate of forests in different parts of the world (Maclean and Klinges, 2021), the robustness and accuracy of those estimates are hard to evaluate in forest types with no or insufficient available field data. Hence, monitoring canopy climate is critical to improving and validating such climate models. In turn, understanding climatic fluctuations in forest canopies is essential to understand and model vegetation-atmosphere interactions, as well as the functional ecology of trees and the incredible diversity of canopy-dwelling organisms found, in particular, in tropical rainforests.

Canopy climate parameters can be estimated from macroclimate with mechanistic models (Maclean, 2020), but akin to other models, calibration and validations demand field measurements (Lembrechts et al., 2020). Recently, a decided leadership and the contribution of a wealth of field measurements resulted in a body of global estimates of high temporal and spatial resolution microclimate for soils and near the soil surface (Lembrechts et al., 2021). This integrative research highlighted the divergence between soil microclimate and macroclimate, summarized consistent patterns across biomes, and incentivized using microclimate to tackle ecological research in the frame imposed by global change. For the canopy, a recent mechanistic model can estimate climate conditions from a climate input and from a series of canopy descriptors (Maclean and Klinges, 2021), however remote and under-described forests configure challenging applications of such models. While extrapolated and modeled macroclimate estimates have supported a generation of studies assessing the effects of climate on organisms and ecosystems (Suggitt et al., 2017), the divergence between macroclimate and climate of specific habitats (Lembrechts and Lenoir, 2020) can obscure the efforts to interpret the impact of climate change on organismal responses (Suggitt et al., 2017; Lembrechts and Lenoir, 2020). Therefore, high-resolution microclimate records constitute a relevant input to unveil ecological nuances of the habitat where they were gathered.

Tropical regions host vast forested areas, like the Amazon, yet detailed canopy climate records for these forests remain scattered (e.g., Löbs et al., 2020). Here, we present a set of climate measurements with high temporal resolution obtained in the canopy of the forest in Yasuni National Park, Ecuador, a global biodiversity hotspot (Bass et al., 2010). Data were collected within the crowns of eight canopy trees, in the Johansson (1974) zone corresponding to the middle canopy. We monitored temperature, relative humidity, photosynthetically active radiation (PAR), and leaf wetness, and we derived the vapor pressure deficit

(VPD). In selected crowns, we additionally registered precipitation, solar radiation, and wind speed and direction. Despite several data gaps due to the harsh conditions for electronics in the forest coupled with logistical challenges, we compiled canopy climate series with more than 300 days of data.

We anticipate that these data series will enrich the view and methodological possibilities of ecologists studying the wealth of organisms dwelling in the canopy of this and other tropical lowland forests. Even if the structure of this canopy remains relatively stable despite recent climate warming trends (Nabe-Nielsen and Valencia, 2020), the biology, ecology, and phenology of its inhabitants may lead to new ecological dynamics and emergent properties (Pincebourde et al., 2016). We encourage using these data series to assess organismal responses of specific organism groups to short-term canopy climate. It is likely that a modeling approach can assess how relevant are fine temporal resolution climate patterns for organismal responses (Lembrechts et al., 2019).

The section below corresponds to the Metadata of our climate data series. Given the potential use of these data in ecological studies, the metadata follows the standard descriptors suggested by Michener et al. (1997), excluding non-applicable fields to avoid redundancies while maintaining the suggested numbering system.

2. Metadata

2.1. Class I. Data set descriptors

A. Data set identity:

High-resolution tropical rain-forest canopy climate data

B. Data set identification codes:

Suggested Data set Identify Codes.

“S1R_Canopy_Climate_2019–20.csv,” “S1V_Canopy_Climate_2019–20.csv,”

“S2R_Canopy_Climate_2019–20.csv,” “S2V_Canopy_Climate_2019–20.csv,”

“S3R_Canopy_Climate_2019–20.csv,” “S3V_Canopy_Climate_2019–20.csv,”

“S4R_Canopy_Climate_2019–20.csv,” “S4V_Canopy_Climate_2019–20.csv,”

“Ridges_Canopy_Climate.csv,” “Valleys_Canopy_Climate.csv,” and “Yasuni_Canopy_Climate.csv” (DataS1).

C. Data set description

I. Originators:

1. Monica B. Berdugo

University of Marburg, Faculty of Geography, Ecological Plant Geography, Deutschhausstraße 10, D-35032, Marburg, Germany

2. Maaïke Bader

University of Marburg, Faculty of Geography, Ecological Plant Geography, Deutschhausstraße 10, D-35032, Marburg, Germany

3. Jörg Bendix

University of Marburg, Faculty of Geography, Laboratory for Climatology and Remote Sensing, Deutschhausstrasse 12, D-35032 Marburg, Germany.

2.2. Class II. Research origin descriptors

A. Overall project description:

1. Identity:

A global approach to analyze the extent of the newly detected Tropical Lowland Cloud Forest (TLCF) based on a large-scale analysis of fog frequency and epiphyte growth, with a special focus on South America

2. Originators:

The TLCF project was coordinated by Maaïke Bader, lead of the Ecological Plant Geography laboratory, and Jörg Bendix, lead of the Laboratory for Climatology and Remote Sensing; both associated with the Faculty of Geography at the University of Marburg.

3. Period of study:

The project started in 2018 and will end in 2022.

4. Objectives:

Mapping and validating the occurrence of fog and modeled abundance patterns of epiphytes in tropical lowland forest areas using remote sensing, field observations, and modeling.

5. Source of funding:

This research was funded by the German Research Foundation – DFG, grants BA 3843/7–1, BE 1780/48–1, and LE 3990/1–1. Deutsche Forschungsgemeinschaft e.V. Kennedyallee 40, 53175 Bonn, Germany.

B. Specific subproject description

1. Site description

a. Site type: Well-preserved tropical rainforest.

b. Geography: Sites were located near the Yasuní Scientific Station (YSS) in Amazonian Ecuador (Figure 1). The YSS is located in the Orellana province (0°40'27''S 76°23'50''W, ~230 m a.s.l., ~90 ha) to the South of the Tiputini river.

c. Habitat: Medium crown of eight canopy trees (Table 1).

d. Geology, landform: Modestly undulating terrain, where local valleys and ridges differ by less than 100 m of elevation, with poor and clayey soils originated from weathering of dominant materials of the intersection between two geological shields, Andes and Brazilian (stratified clays and sediments of the Curaray formation from the tertiary; Tschopp, 1953).

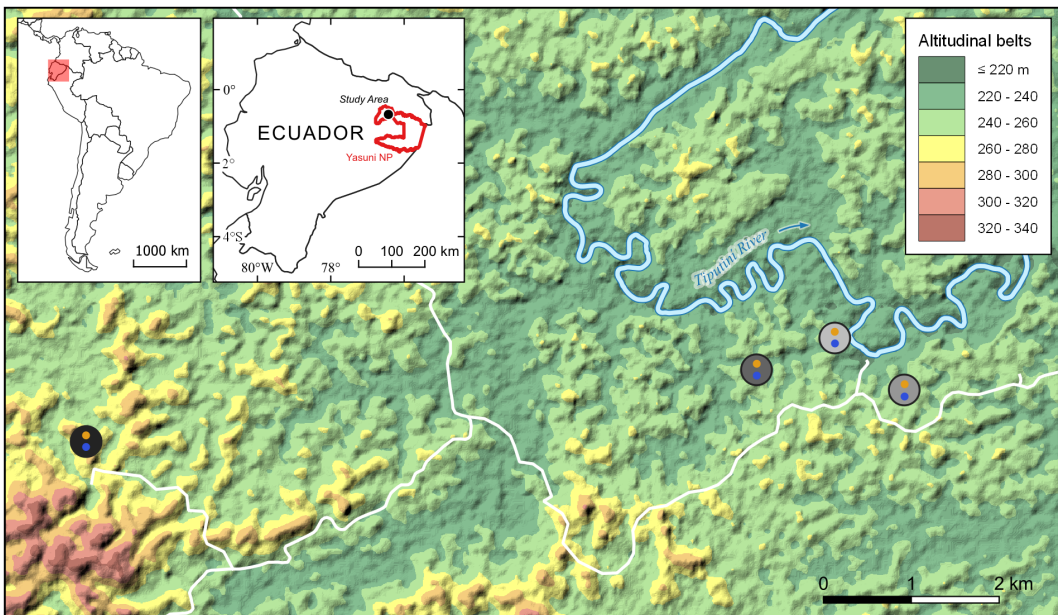


Figure 1. Study area and stratified study design used to monitor climate with a 10-min temporal resolution in the tropical rainforest canopy of the Yasuní National Park, Ecuador. Large circles represent study sites located at different distances from the Tiputini river (black indicates the largest distance and the lightest grey indicates the shorter distance). Two canopy climate stations were established in each site, one in a valley (blue dot) and the other in a ridge (orange dot) as highlighted by colour-keyed altitudinal belts.

Table 1. Identity and dimensions of the trees supporting the canopy climate stations instrumented a given sensor set to monitor the canopy climate of the tropical rain-forest of the Yasuni National Park, Ecuador.

Species	Family	DBH (cm)	Tree height (m)	First branch height (m)	Crown (m)		Canopy cover (%)			Sensor set	D	T	Station
					Radius	Depth	Mean	SD	Range				
<i>Eschweilera coriacea</i>	Lecythidaceae	76.4	28.5	14.0	6.6	14.5	79.2	6.6	68.1–88.7	T, RH, PAR, LW, RAD, Wind			S1V
<i>Trichilia septentrionalis</i>	Meliaceae	41.7	22.3	12.9	4.9	9.4	82.2	4.9	71.1–87.8	T, RH, PAR, LW, RAD, Wind			S1R
<i>Byrsonima putumayensis</i>	Malpigiaceae	55.1	28.0	12.2	8.3	15.8	78.5	6.5	65.9–86.5	T, RH, PAR, LW, PRE, Wind			S2V
<i>Virola duckei</i>	Myristicaceae	86.3	29.9	20.0	6.1	9.9	82.8	4.7	72.7–88.6	T, RH, PAR, LW, PRE, Wind			S2R
<i>Ficus krukovii</i>	Moraceae	104.5	23.0	10.0	8.8	13.0	83.5	2.6	78.6–86.9	T, RH, PAR, LW, PRE			S3V
<i>Eschweilera coriacea</i>	Lecythidaceae	69.7	25.3	15.0	8.4	10.3	78.2	6.7	66.7–87.2	T, RH, PAR, LW, PRE			S3R
<i>Guarea cf. gigantea</i>	Meliaceae	23.9	24.8	19.5	6.1	5.3	80.6	4.8	71.6–85.9	T, RH, PAR, LW, PRE			S4V
<i>Pourouma tomentosa</i>	Urticaceae	55.1	26.7	19.7	8.5	7.0	75.9	3.6	71.3–82.8	T, RH, PAR, LW, PRE			S4R

Note. Coloured bars refer to the stratified study design where S indicates sites and T indicates topography (blue represents valley and orange, ridges). Crown radius is an average calculated from three to four measurements. Canopy cover statistics derived processing 10 pictures taken with a mobile phone and processed in Gap Light Analyzer (GLA Version 2.0; Frazer et al., 2008). Crown depth calculated as the difference between Tree height and Fist branch height.

Abbreviations: DBH, diameter at the breast height; Wind, digital anemometer; LW, leaf wetness; PAR, photosynthetic active radiation; PRE, Generic rain gauge; RAD, Global radiation; RH, relative humidity; T, temperature.

- e. Site history: Forest protected within the Yasuni National Park and distant from active oil well extraction, with the influence of cultural practices of the local indigenous communities belonging to the ethnic group Waorani.
 - f. Climate: The region corresponds to the Holdridge Life Zone of tropical wet forest (Holdridge, 1947, 1964) with a wet equatorial climate with imperceptible seasonality (Bailey, 2014), a mean annual temperature of $\sim 25^{\circ}\text{C}$ and an average annual precipitation of $\sim 2,240$ mm.
2. Experimental or sampling design
 - a. Design characteristics: To monitor canopy climate, eight canopy climate stations were established in a stratified sampling design targeting ridges (four stations) and valleys (four stations). Nearby valley and ridge trees correspond to a site (Table 1). Air temperature, relative humidity, PAR, and leaf wetness were recorded by all canopy climate stations, while precipitation, wind, and global radiation were recorded by selected canopy climate stations (Table 1).
 - b. Data collection period, frequency, etc.: All canopy climate stations measured climate parameters every 30 s and recorded data every 10 min (mean, minimum, maximum, or sampling values of the 20 measurements) between April 2019 and February 2020. However, the different stations and sensors have gaps within this period (Figure 2 and Table 2).
 3. Research methods
 - a. Field/laboratory: We installed eight climate stations, each in the crown of a tree, using adapted climbing techniques (Perry 1978) in the second half of April 2019. These trees belonged to seven species distributed in six botanical families and averaged 64 ± 25.6 cm (mean \pm SD) for DBH, 26 ± 2.7 m of height, and 7.2 ± 1.5 m of crown radius (Table 1); we targeted canopy trees, that is, those immersed in the canopy stratum of the forest—excluding sub-canopy and emergent trees. In each tree, the sensor set (Figure 3) was established in the medium section and upper side of crown branches (i.e., in the middle canopy sensu Johansson 1974). We verified the performance of the climate stations in the lab before installation, and from the ground via WIFI after installation, using the interface provided by the datalogger manufacturer (Device Configuration Utility, 2.21.16 by Campbell scientific). Verifications and data downloading from the ground were performed 1 week, 4 months, and 10 months after installation. After the last verification, we removed the climate stations.

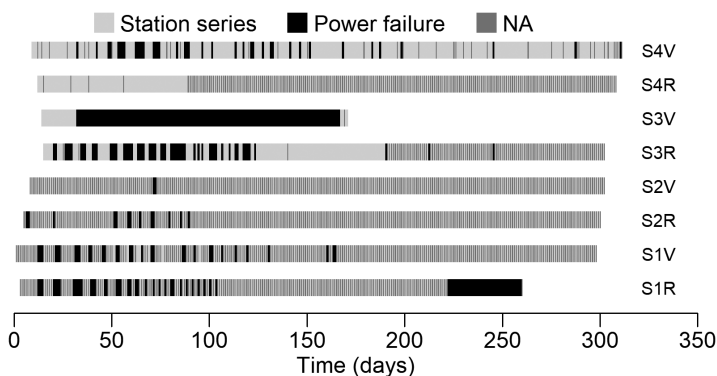


Figure 2. Continuity of the climate series recorded by eight canopy climate station established in the tropical rainforest of the Yasuni National Park, Ecuador. For brevity, we aggregated the data at daily resolution. Power failure corresponded to complete gaps in the series while NA occurred for some of the climate parameters. See descriptive statistics in Table 2.

Table 2. Percentage of NA due to sensor failure (Failure) or due to values out of the variable or sensor range (Outlier) in the climate series recorded by eight canopy climate station established in the tropical rainforest of the Yasuni National Park, Ecuador.

Station	Number of records	NA	T	RH	PAR	LW	PRE	RAD	Wind
S1V	16,492	Failure							
		Outlier		<0.01				75.9	0.2
S1R	23,862	Failure	79.2	79.2					
		Outlier						11.6	0.2
S2V	34,557	Failure							
		Outlier							<0.01
S2R	41,921	Failure							
		Outlier		<0.01					0.1
S3V	17,705	Failure							
		Outlier							
S3R	3,119	Failure				36.4			
		Outlier	0.01	0.02					
S4V	42,588	Failure							
		Outlier	<0.01	0.3	<0.01	0.2			
S4R	23,541	Failure	73.9	73.9		69			
		Outlier							

Note. No NA was identified for station S3V, neither for precipitation, recorded with PRE.

Abbreviations: Wind, digital anemometer; LW, leaf wetness; PAR, photosynthetic active radiation; PRE, generic rain gauge; RAD, global radiation; RH, relative humidity; T, temperature.

- b. Instrumentation: Each canopy climate station consisted of a logger (80 MB CPU drive and 30 MB serial flash storage, configured to host a Wi-Fi network) and its sensor set (Table 1) powered by a solar panel (50 Wp/12VDC, Resun model RSM-50P) and a backup battery (12 V, SunBrigh Battery model 6-FM-20). A controller (Morningstar corporation, model SHS-10) protected the climate station against short circuit, over-current, high voltage, and lightning, and set reverse current at night, that is, shifted the energy source from the solar panel to the battery, charged during light hours. Loggers and sensors (Table 3) were set, programmed, and tested using ShortCut 4.1. (2018) and Device Configuration Utility version 2.21.16 (2019), both by Campbell Scientific. The recording program consisted of registering the different climate parameters every 30 s and logging the data every 10 min. Thus, average, maximum, minimum, standard deviation, and sample values were obtained from 20 measurements.
- c. Permit history: The data presented here were collected in the frame of the research permit 003–2019-IC- PNY- DPAO—PUCE issued by the Ministry of Environment of Ecuador in February 2019 and expired in February 2020.

C. Project personnel:

Monica Berdugo (University of Marburg, Faculty of Geography, Ecological Plant Geography, Marburg, Germany) implemented the ecological work package of the TLCF project, in which the climate was recorded, with the support of Karen Suárez (Federal University of Pernambuco, Biology Department, Laboratory of Plant Taxonomy, Recife, Brazil) and Jorge Déleg (Universidad Técnica Particular de Loja, Departamento de Ciencias Naturales,



Figure 3. Set of sensors used to monitor climate with a 10-min temporal resolution in the tropical rainforest canopy of Yasuni National Park, Ecuador. In each station, a radiation shield (a) protected the sensor for temperature and relative humidity from direct sunshine and rain. The leaf wetness sensor (b) and the sensor for photosynthetic active radiation (c) were placed on the upper side of the medium section of a crown branch. Selected canopy climate stations were instrumented with a generic rain gauge (d), a sensor for global radiation (e), or a digital anemometer (f), as indicated in *Table 1*. Instrument details are provided in *Table 3*.

Herbario HUTPL, Loja, Ecuador); canopy climate installation was supported from the ground by Louise Guérot (University of Marburg, Faculty of Geography, Ecological Plant Geography, Marburg, Germany). Jorge Déleg verified the station performance 4 months after installation. Monica Berdugo removed the climate stations with the support of Ricardo Jaramillo Terán (Universidad San Francisco de Quito, College of Biological and Environmental Sciences, Quito, Ecuador) and Diego Moreno (Universidad Pedagógica y Tecnológica de Colombia, Escuela de Biología, Tunja, Colombia) and developed data curation, verification, and visualization with the support of Leander Heyer (University of Marburg, Faculty of Geography, Ecological Plant Geography).

Table 3. Instrumentation used to monitor the canopy climate of the tropical rain-forest of the Yasuni National Park, Ecuador.

Equipment	Function	Maker	Model	Serial numbers
Data loggers	Implement the program to calculate climate parameters and log the corresponding data	Campbell Scientific	CR300_WIFI	11807, 13980, 13981, 13982, 13984, 13985, 13986, 13987
Temperature and relative humidity sensor	Record minimum, maximum, average, and the standard deviation of air temperature, and minimum and maximum relative humidity. These sensors were protected in 10 plate radiation shields (Figure 3a)	Campbell Scientific	CS215	E21628, E21629, E21630, E21631, E21632, E21633, E21634, E21,635
Dielectric leaf wetness sensor (Figure 3b)	Record the average voltage as well as the period length during which the leaf wetness sensor was dry wet or contaminated. A threshold of <274 mV indicates dry leaves and threshold ≥ 284 indicates wet leaves	Campbell Scientific	LWS	03-615, 03-620, 03-622, 03-626 98600-03-240, 98600-03-241, 98600-03-242, 98600-03-243
Photosynthetically active radiation—PAR sensor (Figure 3c)	Record average, maximum, minimum, and total PAR density	Campbell Scientific	CS310 Quantum Sensor	1664, 1666, 1772, 1773, 1774, 1775, 1776, 1777
Tipping bucket rain gauge (Figure 3d)	Record total precipitation during the recording period (10 min)	ELM	Kalyx	190847, 190848, 190849, 190850, 190851, 190852
Digital thermopile pyranometer (Figure 3e)	Record average solar radiation, average dew point, and a second measurement for average air temperature and its standard deviation	Campbell Scientific	CS320	1835, 1836
Two-dimensional ultrasonic wind sensor (Figure 3f)	Record a sample of wind direction, as well as average, maximum, and minimum wind speed	The Gill	WindSonic4	18480149, 18500164, 18500165, 19480151

2.3. Class III. Data set status and accessibility

A. Status

1. Latest update:
December 2021
2. Latest archive date:
February 2020
3. Metadata status:
August 2020
4. Data verification:

Data were checked in by the authors. In each data series, a variable of each climate parameter was plotted to identify gaps and suspicious data in the records, suggesting partial or definitive sensor failure. This data exploration was supported by field notes taken at the time of

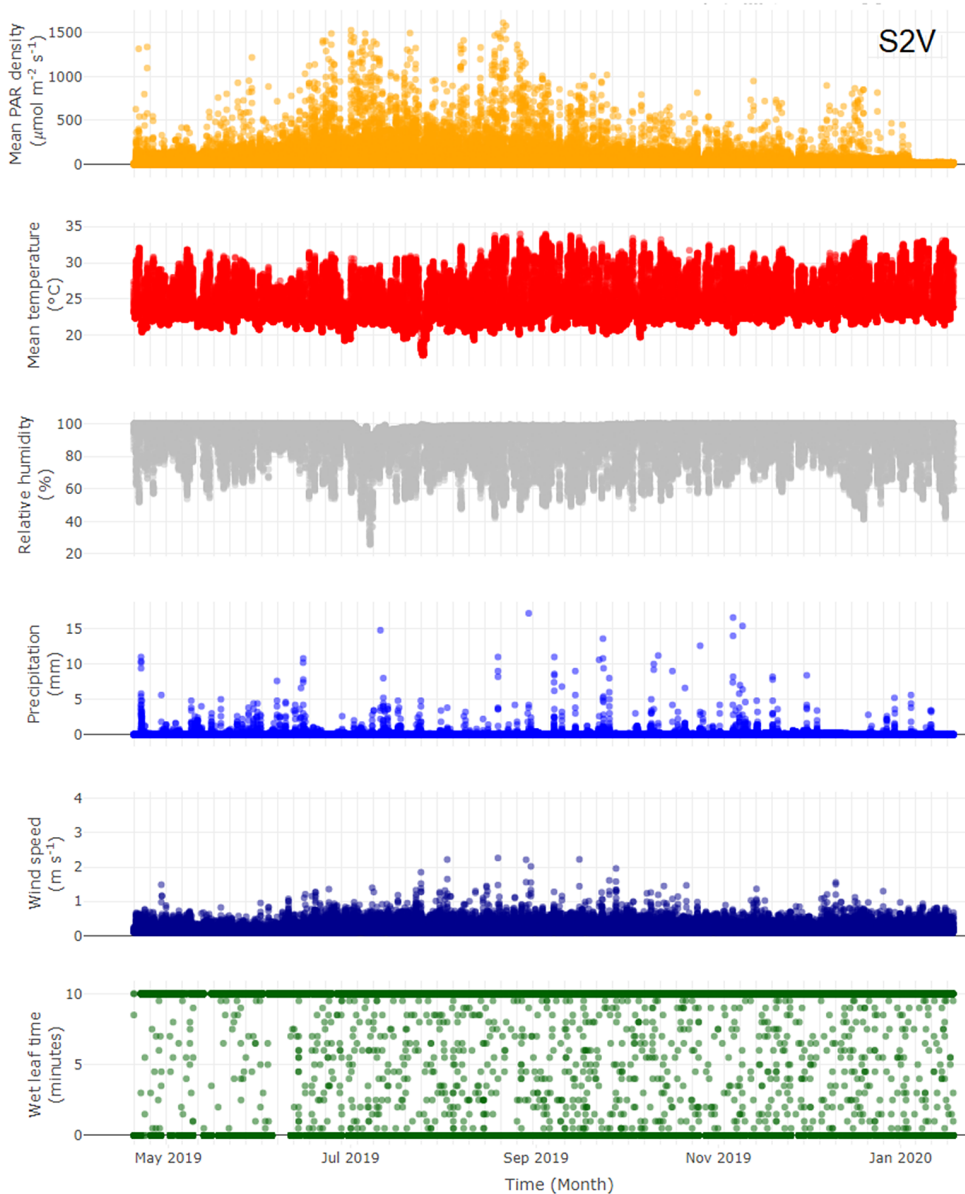


Figure 4. Example of a multiplot after the data verification process, corresponding to station S2V, recording climate every 10-min in the tropical rainforest canopy of the Yasuni National Park, Ecuador. Following the suggestions by the sensor maker (Dielectric leaf wetness sensor, Campbell Scientific), we set the threshold <274 mV to indicate dry and $> = 284$ to indicate wet leaves.

removing the stations (e.g., “rain gauge clogged with canopy debris,” “rain gauge broken; the rain collector is absent,” “climate station box colonized by termites,” “logger under water within the climate station box”). To ease comparisons among stations and sites, data series were aligned, and suspicious data were labeled as NA (R script `Data_Compilation.Rmd`). By the end of the data verification process, the data series contained only trustable data (Figure 4).

B. Accessibility

1. Storage location and medium:

Data files and R scripts of the developed open-source tools are stored in Dryad (https://datadryad.org/stash/share/saMwQoZF81_wT5Gyxm_W2QGfzqGiaeG9nHOVjvfwMT4).

In addition, raw data are stored in the data warehouse of the Laboratory for Climatology and Remote Sensing (LCRS) at the Faculty of Geography of the University of Marburg.

2. Contact person(s):

Monica B. Berdugo, University of Marburg, Faculty of Geography, Ecological Plant Geography, Deutschhausstraße 10, D-35032, Marburg, Germany, phone: +4,906,421 2,824,187, berdugom@staff.uni-marburg.de and biobibiana@yahoo.com.

Maaïke Bader, University of Marburg, Faculty of Geography, Ecological Plant Geography, Deutschhausstraße 10, D-35032, Marburg, Germany, phone: +4,906,421 2,828,952, maaike.bader@uni-marburg.de

3. Copyright restrictions:

None

4. Proprietary restrictions:

There is no restriction for using data from this data paper, as long as the data paper is cited as the source of the information used.

C. Costs:

None.

2.4. Class IV. Data structural descriptors

A. Data set file

1. Identity:

S1V_Canopy_Climate_2019–20.csv.
 S1R_Canopy_Climate_2019–20.csv.
 S2V_Canopy_Climate_2019–20.csv.
 S2R_Canopy_Climate_2019–20.csv.
 S3V_Canopy_Climate_2019–20.csv.
 S3R_Canopy_Climate_2019–20.csv.
 S4V_Canopy_Climate_2019–20.csv.
 S4R_Canopy_Climate_2019–20.csv.
 Yasuni_Canopy_Climate_2019_20.csv.
 Ridges_Canopy_Climate_2019_20.csv.
 Valleys_Canopy_Climate_2019_20.csv.
 Data_Compilation.Rmd.
 Dashboard_CanopyClimate.Rmd.
 Dashboard_CanopyClimate.html.
 Filtering_CanopyClimate.Rmd.

2. Size:

Data size details are presented in [Table 4](#).

3. Format and storage mode:

Comma-separated values (.csv), R Markdown scripts (.Rmd) and outputs (.html).

4. Header information:

Data series of stations in the same site (e.g., S1V and S1R) share headers (See [Table 4](#) in Section B, *Variable information*)

5. Alphanumeric attributes:

Mixed (See [Table 4](#) in Section B, *Variable information*).

B. Variable information

The details of the climatic variables included in the data are summarized in [Table 5](#).

Table 4. Data structural descriptor.

File	Number of records	Record length (days)	Size (KB)
S1R_Canopy_Climate_2019–20.csv	16,492	115	3,090
S1V_Canopy_Climate_2019–20.csv	23,862	166	5,591
S2R_Canopy_Climate_2019–20.csv	34,557	240	7,426
S2V_Canopy_Climate_2019–20.csv	41,921	291	8,929
S3R_Canopy_Climate_2019–20.csv	17,705	123	3,242
S3V_Canopy_Climate_2019–20.csv	3,119	22	564
S4R_Canopy_Climate_2019–20.csv	42,588	296	6,006
S4V_Canopy_Climate_2019–20.csv	23,541	164	4,337
Ridges_Canopy_Climate_2019–20.csv	44,680	302	7,419
Valleys_Canopy_Climate_2019–20.csv	44,680	268	7,852
Yasuni_Canopy_Climate_2019–20.csv	44,680	306	8,379
Data_Compilation_REDS.Rmd	—	—	35
Dashboard_CanopyClimate_R.Rmd	—	—	31
Dashboard_CanopyClimate_R.html			12,445
Filtering_CanopyClimateR.Rmd	—	—	28

Note. Size of the data series of canopy climate of the tropical rain-forest of the Yasuni National Park, Ecuador along to the size of their companion Markdown scripts.

C. Data anomalies:

In the original data series, absent data were filled with NA either by the data logger or during the data verification process, where suspicious data points were replaced by NA. In the derived data series, absent data were filled with NA during the data compilation process.

2.5. Class V. Supplemental descriptors

A. Data acquisition

Automated data loggers.

B. Quality assurance/quality control procedures:

The original data series went through a data verification process while the derived data series resulted from a data compilation process.

The data verification, including the calculation of derived variables, consisted of four steps: (a) visualization and diagnosis of suspicious data, that is, those exceeding the possible values for the climate parameter in the locality or those resulting from sensor failure (for instance, PAR that was above zero during night hours), resulting from malfunctioning of specific sensors; (b) replacement of suspicious data with NA; (c) calculation of derived climate variables (Table 5), average relative humidity as the mean value of the recorded relative humidity variables (maximum and minimum), VPD derived from average relative humidity and average air temperature following Fenton and Frego (2005), calculated dew point (DewPtC) derived from average air temperature and average relative humidity following Lawrence (2005); and transformation of solar radiation data, recorded in kWm^2 , to W/m^2 , because this is the most commonly used unit; and (d) creation of fields used to filter data, that is, Date, Hour, and DateHour (Table 4), by using functions of R base (trunc; R Core Team, 2020), and

Table 5. Variable information for the canopy climate data series of the tropical rain-forest of the Yasuni National Park, Ecuador.

Variable identity	Variable definition	Units	Range	Stations series				Aggregated series		
				S1V S1R	S2V S2R	S3V S3R	S4V S4R	RCC	VCC	YCC
datetime	Record date and time (format yyyy-mm-dd hh:mm:ss)			x	x	x	x	x	x	x
Date	Date derived from the datetime field during the data verification to filter or summarize data at the date resolution (format yyyy-mm-dd)			x	x	x	x	x	x	x
Hour	Hour derived from the datetime field during the data verification to filter or summarize data at the hour resolution (format hh)			x	x	x	x	x	x	x
DateHour	DateHour derived from the datetime field during the data verification to filter or summarize data at the hour resolution within a given date (format yyyy-mm-dd hh)			x	x	x	x			
record	Consecutive record number according to datalogger			x	x	x	x			
BattV	Minimum value of the battery	V	0–14.3	x	x	x	x			
LWmV_Avg	Average leaf wetness	mV	257.7–1,250.0	x	x	x	x	x	x	x
LWMDry_Tot	Period length during which the leaf wetness sensor was dry	Minutes	0–10	x	x	x	x	x	x	x
LWMCon_Tot	Period length during which the leaf wetness sensor was contaminated	Minutes	0–10	x	x	x	x	x	x	x
LWMWet_Tot	Period length during which the leaf wetness sensor was wet	Minutes	0–10	x	x	x	x	x	x	x
PAR_Den_Avg	Average photosynthetically active radiation (PAR) density	umol/(s m ²)	0–1,756	x	x	x	x	x	x	x
PAR_Den_Max	Maximum PAR density	umol/(s m ²)	0–2,158	x	x	x	x	x	x	x
PAR_Den_Min	Minimum PAR density	umol/(s m ²)	0–1,508	x	x	x	x	x	x	x
PAR_Tot_Tot	Total PAR density recorded in 10 min	mmol/(s m ²)	0–1,053.7	x	x	x	x	x	x	x
SlrkW_Avg	Average solar radiation	W/m ²	0–432	x				x	x	x

Table 5. Continued

Variable identity	Variable definition	Units	Range	Stations series				Aggregated series		
				S1V S1R	S2V S2R	S3V S3R	S4V S4R	RCC	VCC	YCC
DewPtC_Avg	Average dew point	°C	5.1–27.72	x				x	x	x
LogTC_AVG	Average temperature of the datalogger	°C	19.24–40.67	x	x	x	x			
BoxTC_AVG	Average temperature within the station box (Figure 5)	°C	18.7–38.59	x	x	x	x			
AirTC_Avg	Average air temperature	°C	17.28–33.96	x	x	x	x	x	x	x
AirTC_Max	Maximum air temperature	°C	17.30–34.40	x	x	x	x	x	x	x
AirTC_TMx	Date and time at which maximum air temperature was registered			x	x	x	x			
AirTC_Min	Minimum air temperature	°C	12.84–33.74	x	x	x	x	x	x	x
AirTC_TMn	Date and time at which minimum air temperature was registered			x	x	x	x			
AirTC_Std	Standard deviation of the air temperature	°C	0.000–1.924	x	x	x	x			
RH_Max	Maximum air relative humidity	%	26.28–100.00	x	x	x	x	x	x	x
RH_Min	Minimum air relative humidity	%	20.01–100.00	x	x	x	x	x	x	x
CS320_Temp_Avg	Average air temperature recorded by the pyranometer	°C	17.15–33.89	x						
CS320_Temp_Std	Standard deviation of the air temperature recorded by the pyranometer	°C	0.000–1.341	x						
WindDir	Sample of wind direction	°	0–359	x	x			x	x	x
WS_ms_S_WVT	Wind speed vector calculated as the mean of the horizontal speed for 10 samples taken during the recording period, using WS_ms as reference wind speed	m/s	0.01–3.16	x						

Table 5. *Continued*

Variable identity	Variable definition	Units	Range	Stations series				Aggregated series		
				S1V S1R	S2V S2R	S3V S3R	S4V S4R	RCC	VCC	YCC
WindDir_D1_WVT	Wind direction vector calculated as the mean of the horizontal direction for 10 samples taken during the recording period, using WindDir as reference wind direction		0–359	x						
WindDir_SD1_WVT	Standard deviation vector WindDir_D1_WVT, using WindDir as the reference wind direction		0–89.3	x						
WS_ms_Avg	Average wind speed	m/s	0–4.10	x	x			x	x	x
WS_ms_Max	Maximum wind speed	m/s	0–12.70	x	x			x	x	x
WS_ms_Min	Minimum wind speed	m/s	0–1.60	x	x			x	x	x
PCP	Total precipitation	mm	0–21.6		x	x	x	x	x	x
RH_Avg	Average relative humidity calculated as the mean value from the records of RH_Max and RH_Min	%	26–100	x	x	x	x	x	x	x
VPD	Vapor pressure deficit calculated as $6.1078^{\exp(17.269 \times \text{AirTC_Avg}/(237.3 + \text{AirTC_Avg}))} \times (1 - \text{RH_Avg}/100)$	hPa	0–29.6	x	x	x	x	x	x	x
DewPtC	Dew point calculated as $\text{AirTC_Avg} - ((100 - \text{RH_Avg})/5)$, following Lawrence (2005)	°C	7.3–27.3	x	x	x	x	x	x	x

Abbreviations: RCC, derived data series aggregating climate records for ridges; VCC, derived data series aggregating climate records for valleys; YCC, derived data series aggregating climate records for the forest.

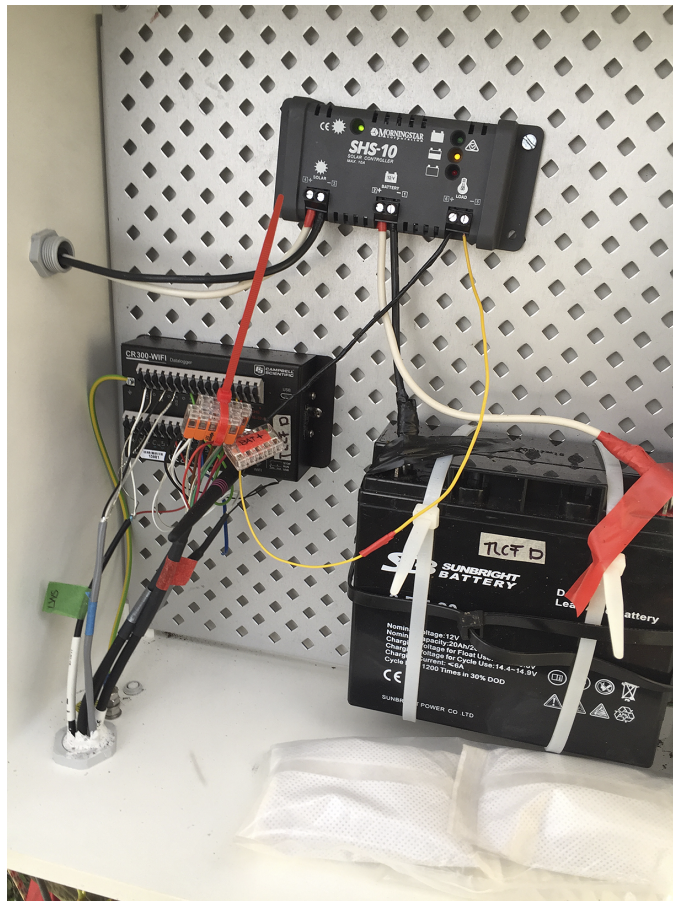


Figure 5. Appearance of a box station (S2R) used to monitor canopy climate with a 10-min temporal resolution in the tropical rainforest canopy of the Yasuni National Park, Ecuador. *Tables 2 and 4 detail equipment and station components.*

“lubridate”(hour; Grolemund and Wickham, 2011) and “chron” (as.chron; James and Hornik, 2020) R packages.

The data compilation consisted of three steps: (a) temporally aligning series for each climate parameter; (b) assigning a value for each climate parameter to each timestep, by either copying the value recorded by a single station or calculating a mean value when two or more stations registered that parameter; absent data were filled with NA; and (c) writing the aggregated data series as an output (in format csv file).

C. Related materials:

None

D. Computer programs and data-processing algorithms:

Data were downloaded using the logger software (Campbell Scientific), while data verification and processing were performed using R (see details in literal B, Quality assurance/quality control procedures, above and in the R scripts: Data_Compilation.Rmd, Dashboard_CanopyClimate.Rmd, and Filtering_CanopyClimate.Rmd).

E. Archiving

1. Archival procedures: Description of how data are archived for long-term storage and access
2. Redundant archival sites: Locations and procedures followed

- F. Publications and results:
None.
- G. History of data set usage
1. Data request history:
None.
 2. Data set update history:
First update in August 2019, second update in February 2020.
 3. Review history:
None.
 4. Questions and comments from secondary users:
None.

3. Conclusion

The main practical lesson from this data collection and compilation is that sustaining cooperation with local researchers is critical to strengthen our capabilities toward understanding ecological processes occurring in tropical canopies, as likewise suggested by Haelewaters et al. (2021). This lesson highlights the need for budgeting qualified partners to ensure proper equipment maintenance. Then, relocating a part of the available budget toward qualified colleagues rather than to equipment would likely result in a more complete and clean raw data series. We observed that equipment becomes less reliable as forest growth occurs in or around critical components of sensors and electronics, including the power supply.

Abbreviations

PAR photosynthetically active radiation
VPD vapor pressure deficit

Acknowledgments. The authors thank the invaluable logistical support by Carlos Padilla, David Lasso, and the Yasuní Scientific Station staff of the Pontifical Catholic University of Ecuador and by Glenda Mendieta-Leiva and Nada Nikolić, members of the Ecological Plant Geography group of the Faculty of Geography at the University of Marburg. Special acknowledgements also for the excellent tree climbing training provided by Vicki Tough and Jeremy Davies of Sylvana ALTA Ltd, and for the cartographic work by Christiane Enderle.

Data Availability Statement. Data files and R scripts of the developed open-source tools are stored in Dryad (https://datadryad.org/stash/share/saMwQoZF81_wT5Gyxm_W2QGfzqGiaeG9nHOVjvfwMT4).

Author Contributions. Conceptualization: M.B.B., K.Y.S.C., M.Y.B.; Data curation: M.B.B., L.H., J.D.; Data visualization: M.B.B., L.H.; Funding acquisition: M.Y.B., J.B.; Investigation: M.B.B., K.Y.S.C., M.Y.B.; Methodology: M.B.B., K.Y.S., M.Y.B.; Project administration: M.B.B., M.Y.B.; Resources and supervision: M.Y.B.; Software: M.B.B., L.H.; Writing original draft: M.B.B. All authors approved the final submitted draft.

Ethics Statement. The research meets all ethical guidelines, including adherence to the legal requirements of the study country.

Funding Statement. This data paper was funded by the German Research Foundation –DFG– (BA 3843/7–1, BE 1780/48–1 & LE 3990/1–1).

Competing Interests. The authors declare no competing interests exist.

References

- Bailey RG (2014) *Ecoregions*, 2nd Edn. New York: Springer. <https://doi.org/10.1007/978-1-4939-0524-9>
- Barker MG and Pinard MA (2001) Forest canopy research: Sampling problems, and some solutions. *Plant Ecology* 153, 23–38.
- Bass MS, Finer M, Jenkins CN, Kreft H, Cisneros-Heredia DF, McCracken SF, Pitman NC, English PH, Swing K, Villa G, Di Fiore A, Voigt CC and Kunz TH (2010) Global conservation significance of Ecuador's Yasuní National Park. *PLoS ONE* 5, e8767. <https://doi.org/10.1371/journal.pone.0008767>

- Fenton, N. J., & Frego, K. A. (2005). Bryophyte (moss and liverwort) conservation under remnant canopy in managed forests. *Biological Conservation*, 122(3), 417–430. <https://doi.org/10.1016/j.biocon.2004.09.003>
- Frazer GW, Canham CD and Lertzman KP (2008) *Gap Light Analyzer (GLA): Imaging Software to Extract Canopy Structure and Gap Light Transmission Indices from True-Colour Fisheye Photographs, User's Manual and Program Documentation*. Burnaby: Simon Fraser University. Available at <http://www.rem.sfu.ca/forestry/downloads/Files/GLAV2UsersManual.pdf> (accessed 28 February 2019).
- Grolemund G and Wickham H (2011) Dates and times made easy with lubridate. *Journal of Statistical Software* 40(3), 1–25. Available at <https://www.jstatsoft.org/v40/i03/>.
- Haelewaters D, Hofmann TA and Romero-Olivares AL (2021) Ten simple rules for global north researchers to stop perpetuating helicopter research in the Global South. *PLoS Computational Biology* 17, 1–8. <https://doi.org/10.1371/journal.pcbi.1009277>
- Holdridge LR (1947) Determination of world plant formations from simple climatic data. *Science* 105, 367–368. <https://doi.org/10.1126/science.105.2727.367>
- Holdridge LR (1964) Life zone ecology. In *Life zone ecology*. rev. ed.
- James D and Hornik K (2020) chron: Chronological Objects which Can Handle Dates and Times. R package version 2.3–56.
- Johansson D (1974) Ecology of vascular epiphytes in West African rain forests. *Acta Phytogeographica Suecica* 59, 136.
- Lawrence MG (2005) The relationship between relative humidity and the dewpoint temperature in moist air: A simple conversion and applications. *Bulletin of the American Meteorological Society* 86, 225–234. <https://doi.org/10.1175/BAMS-86-2-225>
- Lembrechts JJ, Aalto J, Ashcroft MB, De Frenne P, Kopecký M, Lenoir J, Luoto M, Maclean IMD, Rouspard O, Fuentes-Lillo E, García RA, Pellissier L, Pitteloud C, Alatalo JM, Smith SW, Björk RG, Muffler L, Ratier Backes A, Cesarz S, Gottschall F, Okello J, Urban J, Plichta R, Svátek M, Phartyal SS, Wipf S, Eisenhauer N, Puşcaş M, Turtureanu PD, Varlagin A, Dimarco RD, Jump AS, Randall K, Dorrepaal E, Larson K, Walz J, Vitale L, Svoboda M, Finger Higgens R, Halbritter AH, Curasi SR, Klupar I, Koontz A, Pearse WD, Simpson E, Stenkovski M, Jessen Graae B, Vedel Sørensen M, Høye TT, Fernández Calzado MR, Lorite J, Carbognani M, Tomaselli M, Forte TGW, Petraglia A, Haesen S, Somers B, Van Meerbeek K, Björkman MP, Hylander K, Merinero S, Gharun M, Buchmann N, Dolezal J, Matula R, Thomas AD, Bailey JJ, Ghosn D, Kazakis G, de Pablo MA, Kempainen J, Niittynen P, Rew L, Seipel T, Larson C, Speed JDM, Ardö J, Cannone N, Guglielmin M, Malfasi F, Bader MY, Canessa R, Stanisci A, Kreyling J, Schmeddes J, Teuber L, Aschero V, Čiliak M, Máliš F, De Smedt P, Govaert S, Meeussen C, Vangansbeke P, Gigauri K, Lamprecht A, Pauli H, Steinbauer K, Winkler M, Ueyama M, Nuñez MA, Ursu TM, Haider S, Wedegärtner REM, Smiljanic M, Trouillier M, Wilmking M, Altman J, Brúna J, Hederová L, Macek M, Man M, Wild J, Vittoz P, Pärtel M, Barančok P, Kanka R, Kollár J, Palaj A, Barros A, Mazzolari AC, Bauters M, Boeckx P, Benito Alonso JL, Zong S, Di Cecco V, Sitková Z, Tielbörger K, van den Brink L, Weigel R, Homeier J, Dahlberg CJ, Medinets S, Medinets V, De Boeck HJ, Portillo-Estrada M, Verryckct LT, Milbau A, Daskalova GN, Thomas HJD, Myers-Smith IH, Blonder B, Stephan JG, Descombes P, Zellweger F, Frei ER, Heinesch B, Andrews C, Dick J, Siebicke L, Rocha A, Senior RA, Rixen C, Jimenez JJ, Boike J, Pauchard A, Scholten T, Scheffers B, Klings D, Basham EW, Zhang J, Zhang Z, Géron C, Fazlioglu F, Candan O, Sallo Bravo J, Hrbacek F, Laska K, Cremonese E, Haase P, Moyano FE, Rossi C and Nijs I (2020) SoilTemp: A global database of near-surface temperature. *Global Change Biology* 26, 6616–6629. <https://doi.org/10.1111/gcb.15123>
- Lembrechts JJ and Lenoir J (2020) Microclimatic conditions anywhere at any time! *Global Change Biology* 26, 337–339. <https://doi.org/10.1111/gcb.14942>
- Lembrechts JJ, Nijs I and Lenoir J (2019) Incorporating microclimate into species distribution models. *Ecography* 42, 1267–1279. <https://doi.org/10.1111/ecog.03947>
- Lembrechts JJ, van den Hoogen J, Aalto J, Ashcroft MB, De Frenne P, Kempainen J, Kopecký M, Luoto M, Maclean IMD, Crowther TW, Bailey JJ, Haesen S, Klings DH, Niittynen P, Scheffers BR, Van Meerbeek K, Aartsma P, Abdalaze O, Abedi M, Aerts R, Ahmadian N, Ahrends A, Alatalo JM, Alexander JM, Allonsius CN, Altman J, Ammann C, Andres C, Andrews C, Ardö J, Arriga N, Arzac A, Aschero V, Assis RL, Assmann JJ, Bader MY, Bahalkeh K, Barančok P, Barrio IC, Barros A, Barthel M, Basham EW, Bauters M, Bazzichetto M, Marchesini LB, Bell MC, Benavides JC, Benito Alonso JL, Berauer BJ, Bjerke JW, Björk RG, Björkman MP, Björnsdóttir K, Blonder B, Boeckx P, Boike J, Bokhorst S, Brum BNS, Brúna J, Buchmann N, Buysse P, Camargo JL, Campoe OC, Candan O, Canessa R, Cannone N, Carbognani M, Carnicer J, Casanova-Katny A, Cesarz S, Chojnicki B, Choler P, Chown SL, Cifuentes EF, Čiliak M, Contador T, Convey P, Cooper EJ, Cremonese E, Curasi SR, Curtis R, Cutini M, Dahlberg CJ, Daskalova GN, de Pablo MA, Della Chiesa S, Dengler J, Deronde B, Descombes P, Di Cecco V, Di Musciano M, Dick J, Dimarco RD, Dolezal J, Dorrepaal E, Dušek J, Eisenhauer N, Eklundh L, Erickson TE, Erschbamer B, Eugster W, Ewers RM, Exton DA, Fanin N, Fazlioglu F, Feigenwinter I, Fenu G, Ferlian O, Fernández Calzado MR, Fernández-Pascual E, Finckh M, Higgens RF, Forte TGW, Freeman EC, Frei ER, Fuentes-Lillo E, García RA, García MB, Géron C, Gharun M, Ghosn D, Gigauri K, Gobin A, Goded I, Goedeke M, Gottschall F, Goulding K, Govaert S, Graae BJ, Greenwood S, Greiser C, Grelle A, Guénard B, Guglielmin M, Guillemot J, Haase P, Haider S, Halbritter AH, Hamid M, Hammerle A, Hampe A, Haugum SV, Hederová L, Heinesch B, Helfter C, Hepenstrick D, Herberich M, Herbst M, Hermanutz L, Hik DS, Hoffrén R, Homeier J, Hörtnagl L, Høye TT, Hrbacek F, Hylander K, Iwata H, Jackowicz-Korczynski MA, Jactel H, Järveoja J, Jastrzębowski S, Jentsch A, Jiménez JJ, Jónsdóttir IS, Jucker T, Jump AS, Juszcak R, Kanka R, Kašpar V, Kazakis G, Kelly J, Khuroo AA, Klemetsson L, Klisz M, Kljun N, Knohl A, Kobler J, Kollár J, Kotowska MM, Kovács B, Kreyling J, Lamprecht A, Lang SI, Larson C, Larson K, Laska K, le Maire G, Leihy RI, Lens L, Liljebladh B, Lohila A, Lorite J, Loubet B, Lynn J, Macek M, Mackenzie R, Magliulo E, Maier R, Malfasi F, Máliš F, Man M, Manca G, Manco A, Manise T, Manolaki P, Marciniak

- F, Matula R, Mazzolari AC, Medinets S, Medinets V, Meeussen C, Merinero S, Mesquita RCG, Meusburger K, Meysman FJR, Michaletz ST, Milbau A, Moiseev D, Moiseev P, Mondoni A, Monfries R, Montagnani L, Moriana-Armendariz M, Morra di Cella U, Mörsdorf M, Mosedale JR, Muffler L, Muñoz-Rojas M, Myers JA, Myers-Smith IH, Nagy L, Nardino M, Naujokaitis-Lewis I, Newling E, Nicklas L, Niedrist G, Niessner A, Nilsson MB, Normand S, Nosoletto MD, Nouvellon Y, Nuñez MA, Ogaya R, Ogee J, Okello J, Olejnik J, Olesen JE, Opedal OH, Orsenigo S, Palaj A, Pampuch T, Panov AV, Pärtel M, Pastor A, Pauchard A, Pauli H, Pavelka M, Pearse WD, Peichl M, Pellissier L, Penczykowski RM, Penuelas J, Petit Bon M, Petraglia A, Phartyal SS, Phoenix GK, Pio C, Pitacco A, Pitteloud C, Plichta R, Porro F, Portillo-Estrada M, Poulénard J, Poyatos R, Prokushkin AS, Puchalka R, Puşcaş M, Radujković D, Randall K, Ratier Backes A, Remmele S, Remmers W, Renault D, Risch AC, Rixen C, Robinson SA, Robroek BJM, Rocha AV, Rossi C, Rossi G, Rouspard O, Rubtsov AV, Saccone P, Sagot C, Sallo Bravo J, Santos CC, Sarneel JM, Scharnweber T, Schmeddes J, Schmidt M, Scholten T, Schuchardt M, Schwartz N, Scott T, Seeber J, Segalin de Andrade AC, Seipel T, Semenchuk P, Senior RA, Serra-Diaz JM, Sewerniak P, Shekhar A, Sidenko NV, Siebicke L, Siegwart Collier L, Simpson E, Siqueira DP, Sitková Z, Six J, Smiljanic M, Smith SW, Smith-Tripp S, Somers B, Sørensen MV, Souza JJLL, Souza BI, Souza Dias A, Spasojevic MJ, Speed JDM, Spicher F, Stanisci A, Steinbauer K, Steinbrecher R, Steinwandter M, Stemkovski M, Stephan JG, Stiegler C, Stoll S, Svátek M, Svoboda M, Tagesson T, Tanentzap AJ, Tanneberger F, Theurillat JP, Thomas HJD, Thomas AD, Tielbörger K, Tomaselli M, Treier UA, Trouillier M, Turtureanu PD, Tutton R, Tyystjärvi VA, Ueyama M, Ujházy K, Ujházyová M, Uogintas D, Urban AV, Urban J, Urbaniak M, Ursu TM, Vaccari FP, Van de Vondel S, van den Brink L, Van Geel M, Vandvik V, Vangansbeke P, Varlagin A, Veen GF, Veenendaal E, Venn SE, Verbeeck H, Verbruggen E, Verheijen FGA, Villar L, Vitale L, Vittoz P, Vives-Inglá M, von Oppen J, Walz J, Wang R, Wang Y, Way RG, Wedegärtner REM, Weigel R, Wild J, Wilkinson M, Wilmking M, Wingate L, Winkler M, Wipf S, Wohlfahrt G, Xenakis G, Yang Y, Yu Z, Yu K, Zellweger F, Zhang J, Zhang Z, Zhao P, Ziemlińska K, Zimmermann R, Zong S, Zryyanov VI, Nijs I and Lenoir J (2022). Global maps of soil temperature. *Global Change Biology* 28, 3110–3144. <https://doi.org/10.1111/gcb.16060>
- Lin D, Xia J and Wan S (2010) Climate warming and biomass accumulation of terrestrial plants: A meta-analysis. *New Phytologist* 188, 187–198. <https://doi.org/10.1111/j.1469-8137.2010.03347.x>
- Löbs N, Walter D, Barbosa CGG, Brill S, Alves RP, Cerqueira GR, de Oliveira Sá M, de Araújo AC, de Oliveira LR, Ditas F, Moran-Zuloaga D, Pires Florentino AP, Wolff S, Godoi RHM, Kesselmeier J, Mota de Oliveira S, Andreae MO, Pöhlker C and Weber B (2020) Microclimatic conditions and water content fluctuations experienced by epiphytic bryophytes in an Amazonian rain forest. *Biogeosciences* 17, 5399–5416. <https://doi.org/10.5194/bg-17-5399-2020>
- Luo Y (2007) Terrestrial carbon–cycle feedback to climate warming. *Annual Review of Ecology, Evolution, and Systematics* 38, 683–712. <https://doi.org/10.1146/annurev.ecolsys.38.091206.095808>
- Maclean IMD (2020) Predicting future climate at high spatial and temporal resolution. *Global Change Biology* 26, 1003–1011. <https://doi.org/10.1111/gcb.14876>
- Maclean IMD and Klings DH (2021) Microclim: A mechanistic model of above, below and within-canopy microclimate. *Ecological Modelling* 451, 109567. <https://doi.org/10.1016/j.ecolmodel.2021.109567>
- Michener WK, Brunt JW, Helly JJ, Kirchner TB and Stafford SG (1997) Nongeospatial metadata for the ecological sciences. *Ecological Applications* 7, 330–342. [https://doi.org/10.1890/1051-0761\(1997\)007\[0330:NMFOTES\]2.0.CO;2](https://doi.org/10.1890/1051-0761(1997)007[0330:NMFOTES]2.0.CO;2)
- Nabe-Nielsen J and Valencia R (2020) Canopy structure and forest understory conditions in a wet Amazonian forest—No change over the last 20 years. *Biotropica* 52, 1121–1126. <https://doi.org/10.1111/btp.12872>
- Nakamura A, Kitching RL, Cao M, Creedy TJ, Fayle TM, Freiberg M, Hewitt CN, Itioka T, Koh LP, Ma K, Malhi Y, Mitchell A, Novotny V, Ozanne CMP, Song L, Wang H and Ashton LA (2017) Forests and their canopies: Achievements and horizons in canopy science. *Trends in Ecology and Evolution* 32, 438–451. <https://doi.org/10.1016/j.tree.2017.02.020>
- O’Grady PA, Tissue DT and Beadle CL (2011) Canopy processes in a changing climate. *Tree Physiology* 31(9), 887–892. <https://doi.org/10.1093/treephys/tpr096>
- Perry, D. (1978). A method of access into the crowns of emergent and canopy trees. *Biotropica* (10):155–157.
- Pincebourde S, Murdock CC, Vickers M and Sears MW (2016) Fine-scale microclimatic variation can shape the responses of organisms to global change in both natural and urban environments. *Integrative and Comparative Biology* 56, 45–61. <https://doi.org/10.1093/icb/icw016>
- R Core Team (2020) *R: A Language and Environment for Statistical Computing*. Vienna, Austria: R Foundation for Statistical Computing. Available at <https://www.R-project.org/>.
- Suggitt AJ, Platts PJ, Barata IM, Bennie JJ, Burgess MD, Bystriakova N, Duffield S, Ewing SR, Gillingham PK, Harper AB, Hartley AJ, Hemming DL, Maclean IMD, Maltby K, Marshall HH, Morecroft MD, Pearce-Higgins JW, Pearce-Kelly P, Phillimore AB, Price JT, Pyke A, Stewart JE, Warren R and Hill JK (2017) Conducting robust ecological analyses with climate data. *Oikos* 126, 1533–1541. <https://doi.org/10.1111/oik.04203>
- Tschopp HJ (1953) Oil explorations in the orient of Ecuador, 1938-1950. *Bulleting of the American Association of Petroleum Geologists* 37, 2303–2347.