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Toward a Unified TreeTalker Data Curation Process

Enrico Tomelleri [1,*], Luca Belelli Marchesini [2], Alexey Yaroslavtsev [3], Shahla Asgharinia [4] and Riccardo Valentini [4]

[1] Faculty of Science and Technology, Free University of Bolzano, Piazza Università 5, 39100 Bolzano, Italy
[2] Forest Ecology Unit, Research and Innovation Centre, Fondazione Edmund Mach, Via E. Mach, 38010 San Michele all'Adige, Italy; luca.belellimarchesini@fmach.it
[3] Department of Ecology, Russian State Agrarian University—Moscow Timiryazev Agricultural Academy, Timiryazevskaya St., 49, 127550 Moscow, Russia; yaroslavtsevam@gmail.com
[4] Department for Innovations in Biological, Agri-Food and Forest Systems (DIBAF), University of Tuscia, Via San Camillo de Lellis 4, 01100 Viterbo, Italy; asgharinia@unitus.it (S.A.); rik@unitus.it (R.V.)
* Correspondence: etomelleri@unibz.it

Abstract: The Internet of Things (IoT) development is revolutionizing environmental monitoring and research in macroecology. This technology allows for the deployment of sizeable diffuse sensing networks capable of continuous monitoring. Because of this property, the data collected from IoT networks can provide a testbed for scientific hypotheses across large spatial and temporal scales. Nevertheless, data curation is a necessary step to make large and heterogeneous datasets exploitable for synthesis analyses. This process includes data retrieval, quality assurance, standardized formatting, storage, and documentation. TreeTalkers are an excellent example of IoT applied to ecology. These are smart devices for synchronously measuring trees' physiological and environmental parameters. A set of devices can be organized in a mesh and permit data collection from a single tree to plot or transect scale. The deployment of such devices over large-scale networks needs a standardized approach for data curation. For this reason, we developed a unified processing workflow according to the user manual. In this paper, we first introduce the concept of a unified TreeTalker data curation process. The idea was formalized into an R-package, and it is freely available as open software. Secondly, we present the different functions available in "ttalkR", and, lastly, we illustrate the application with a demonstration dataset. With such a unified processing approach, we propose a necessary data curation step to establish a new environmental cyberinfrastructure and allow for synthesis activities across environmental monitoring networks. Our data curation concept is the first step for supporting the TreeTalker data life cycle by improving accessibility and thus creating unprecedented opportunities for TreeTalker-based macroecological analyses.

Keywords: IoT; forest ecology; big data; accessibility

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1. Introduction

Technological innovation has frequently been an accelerator for gaining new knowledge in many fields of ecology [1]. The development of Wireless Sensor Network (WSN) technology, combined with the advancements in low-power, high range data transmission, is revolutionizing the approach to environmental monitoring [2]. Such developments, combined with cellular networks capable of supporting massive connectivity with efficient schemes for tethering billions of devices globally, enable Internet of Things (IoT) applications in many fields of science, including ecology [3,4]. This is further advantaged by increasingly ubiquitous connectivity and the extensive coverage provided by the latest generations of communication networks [5]. Thus, such technologies offer new opportunities for collecting continuously consistent environmental and ecophysiological parameters with high temporal frequency across broad spatialized networks [6–8].

The ecological applications of IoT provide different advantages compared to other approaches for environmental monitoring by empowering ecologists to address massive data retrieval in situations where manual collection from multiple and heterogeneous sensors would be time consuming and error-prone. At the same time, diffused networks of environmental sensors allow for conducting measurements with high temporal frequency, even in rough environments or remote experimental sites [9]. Additionally, WSN-based experiments have the possibility for integration with adjacent networks and even with other data streams such as remote sensing [10].

The need for several sensors to be implemented in extended networks requires the usage of low-cost solutions. Such requirement boosts the implementation of open solutions, including open hardware and open software. As a result, IoT technology generally bears unprecedented opportunities for ad hoc customization and community-based development, contributing to the fast diffusion and enhancement of IoT usage in environmental applications [11].

Several smart devices have already supplanted traditional monitoring systems relying on discrete or manual methodologies, giving real-time, continually analyzed, and wirelessly provided data, but different challenges remain unsolved [12]. As a matter of fact, in parallel to increasing ecological data availability, there is a new need to establish and deploy appropriate cyberinfrastructures [8] to enable data science-based research. The first step in designing such an infrastructure is the definition of data curation strategies, including device and data monitoring, quality assurance, storage, analysis, and accessibility. Firstly, a network with many sensors needs the constant monitoring of functionality, especially in harsh environments where an accurate and regular automated control can promptly permit the network manager to act in the case of failure [13]. Additionally, the following crucial step is quality assurance, because the data might suffer from different disturbing factors such as sensor degradation, unstable power availability, and transmission issues [11]. Such factors might generate a disturbed measured signal but could also be the source of missing data or generate duplicates. Secondly, data sourcing from multiple sensors across regional networks needs to include proper and consistent formats [14]. This means adopting self-documenting and recognized standards. This step is of paramount importance for supporting data-sharing and for enabling the final user to proceed with further analyses [15]. Lastly, data are required to be documented, and data access policies should be defined to allow for distribution and accessibility. In detail, accessibility establishes the degree to which researchers can use data. This means that accessible data are not only available but also usable. Therefore, accessibility requires the usage of standard—and possibly self-documenting—formats. In this context, the adoption of a standardized curation approach is fundamental for any Research Data Management plan [16], and it is a milestone for any research hypothesis making use of experimental "big-data" collected across large areas and across different research groups [17]. As mentioned by [18], there is an urgent need for ecologists to establish networks across institutional boundaries to pursue broad scale questions. Thus, in the past few years, the rising data-sharing culture binned uniformed data gathering methods together with data and metadata formats permitted to address regional- to global-scale questions. A good-practice example is the ICOS network, where in situ observations of carbon and other greenhouse gasses (GHG) are continuously collected across 140 measurement stations and 12 European countries according to standardized protocols, processed with a unified processing workflow, and provided to the final user as ICOS data products in a standardized data format [19].

This reasoning showed us the opportunity to develop an open-source toolbox implementing a unified processing workflow for the broad deployment of TreeTalkers (Nature 4.0 SB srl) data within the scientific community. As already demonstrated by the ICOS project in the context of GHG emissions, the presented workflow will support data-sound model development and the inference of forest attributes through the integration of TreeTalker data with complementary data streams [10] and their ultimate feeding into artificial intelligence systems for forestry applications and, eventually, for their contribution to the creation of forest digital twins [20].

2. The TreeTalker

The need to protect forests and technological developments have permitted the development of novel IoT devices for specific applications such as fire and deforestation monitoring. For example, the SeaForest solution is a system for detecting fire, pollution sources, or illegal deforestation based on IoT devices. [21,22] revises the available systems for forest fire detection applications and proposes a novel method based on multi-sensors and cameras. On the other hand, such systems can be deployed to monitor the environment but not multiple parameters related to tree ecophysiology. A more comprehensive approach is required for a better understanding of the resilience of forests to extreme events. The TreeTalker technology provides this opportunity because it is capable of measuring with high frequency and in nearly real-time key processes such as the water consumption, the growth of biomass (diameter), and the health of the leaves. The device consists of a logger enclosed in a plastic case that acquires signals from various sensors (Figure 1). The device is typically installed on a tree trunk at breast height. The current version of the system is described by [6]. It runs on batteries, and it has an average autonomy of up to three months with the default measurement frequency. A separated device equipped solely with a thermohygrometer and a multi-band spectrometer (TT-R) can be placed outside of the canopy for reference. The user can freely program the acquisition rate, which is by default set to hourly, allowing for adaptable and continuous high-frequency environmental monitoring. Raw data are collected via Long Range connection (LoRa) by a master node (the so-called TT-Cloud) and transmitted via the Global System for Mobile Communications (GSM) to a central server. The collected data are centrally saved as digital numbers and require further conversions to be expressed in physical units.

Figure 1. A beech tree monitored with a TreeTalker (power supply not shown).

3. The ttalkR Concept

The ttalkR workflow consists of four subsequential steps (Figure 2). Firstly, it is necessary to retrieve the data relative to a specific mesh of sensors from one or more servers. Secondly, the datasets are merged into four dedicated tables containing detailed information from different classes of devices or specific sensors. One table is for the TT-Cloud, one table is for the data collected from the embedded spectrometers, one table includes all the communication diagnostics, and the last table collects data from all the other sensors. Thirdly, basic quality assurance procedures are applied (i.e., outliers' removal and basic gap filling), followed by the conversions from digital numbers to physical units, which are conducted according to the TreeTalkers' user manual (TT+manual ver. 3.2, September 2020). Lastly, the derived variables are plotted for visualization and saved locally into an SQLite database for further processing.

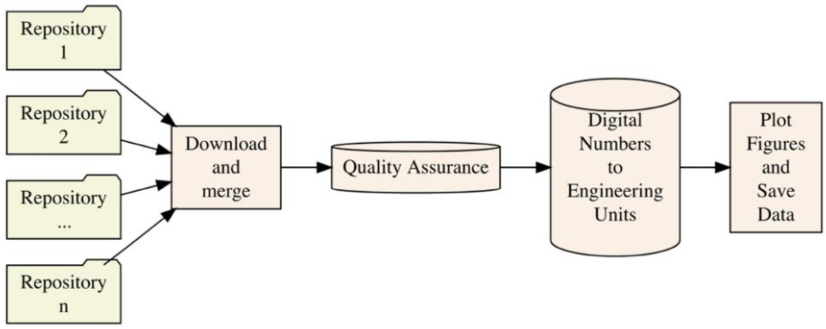

Figure 2. Conceptual workflow of the data curation process within the ttalkR package from the data download to the figures and data saving.

4. Functions of ttalkR

The "ttalkR" package is a collection of functions for curating TreeTalker data. The package is organized in dedicated functions addressing each measured parameter by a TreeTalker device (Figure 3). Such functions are usable between the input function named *ttScrape()* and the output function named *ttOutput()*. The plotting utilities permit the user to visualize the measured parameters' canopy/mesh scale but also the single tree level. While the first approach is useful for gaining an overview at the measurement site, the second approach allows for the identification of anomalous trees and can be used for diagnostic purposes (e.g., for identifying interesting patterns and, eventually, for spotting faulty sensors). Thus, the package can also be deployed for operational site functioning monitoring and maintenance, repair, and operation (MRO).

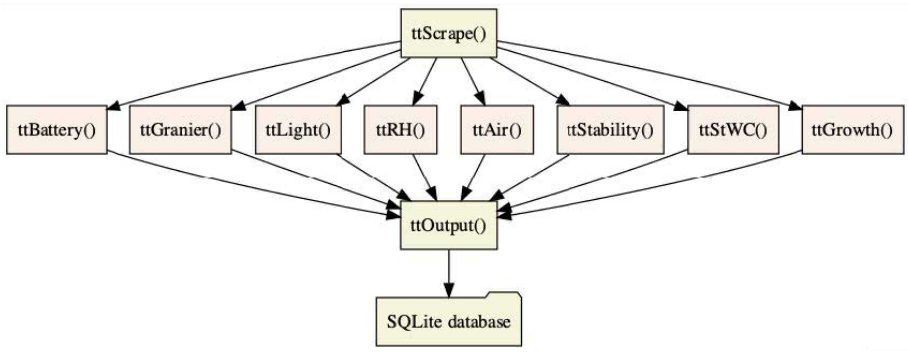

Figure 3. Detailed structure and functions of the ttalkR package. I/O functions are highlighted in green.

4.1. Data Download

The core of the package is formed by the *ttScrape()* function. It downloads TreeTalkers data from specific servers and organizes the different strings into the four aforementioned tables, which are required for further processing. The package was initially developed for the Italian Treetalker network, which also makes use of the standard server initialized by the devices' producer, but it can be deployed for any hosting server by adapting the source URL. The derived tables include information about the (i) status of the master (e.g., battery level and GSM metrics), (ii) communication diagnostics for the connected TreeTalkers (i.e., radio signal strength), (iii) raw data acquired by the spectrometers, and (iv) raw data from all the other attached sensors. The function *ttScrape()* includes a first-tagging of the missing data and removes duplicated fields. Further quality assurance steps are executed in the parameter-specific functions.

4.2. Battery Voltage

The battery voltage of the TreeTalkers within a mesh and the associated master (TTcloud) can be monitored for MRO purposes. Like all the following functions, *ttBattery()* makes use of the data frames created by the *ttScrape()* function. For each TreeTalker, it calculates and plots the battery level consistently with the programmed measurement frequency (Figure 4A). The function considers the bandgap voltage reference of the microcontroller (1.1.v) and the analogue to digital conversion (ADC) values of the bandgap and the battery. No quality assurance is applied to these parameters. As indicated by the producer, the batteries should be recharged at 3500 mV because, below such threshold, the proper functioning of the sensors is not guaranteed (Figure 4A).

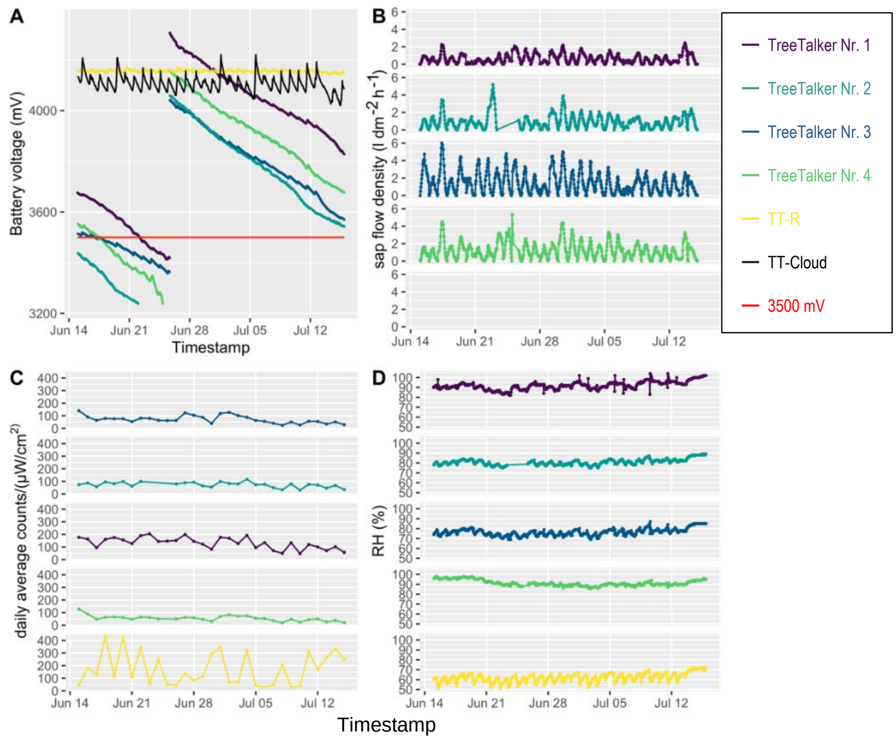

Figure 4. Output of the "ttalkR" plotting utility. (**A**) battery voltage with the indication of the warning threshold (3500 mV); (**B**) sap flow; (**C**) under canopy radiation; (**D**) relative humidity. The example data refer to four TreeTalkers and a TT-R for the period between 14 June 2021 and 14 July 2021. In (**B**), the data from the TT-R are missing because it is a reference device outside of the canopy which is not equipped with the corresponding sensors.

4.3. Sap Flow

Transpiration is a critical process that links the exchange of water, carbon, and energy between the land and the atmosphere, influencing various vegetation–atmosphere feedbacks. Water transfer from the roots to the leaves is driven by transpiration in the form of sap flow through the plant's xylem pathway, and this sap flow influences heat transport in the xylem [23]. The current version (3.2) of the TreeTalker device uses the thermal dissipation method [24] with repeated heating cycles. The default settings foresee 10 min of heating and 50 min of cooling. Probe pairs are inserted in the tree stem with a vertical separation of 10 cm. Normally, the probes are positioned facing north to avoid direct solar heating. Firstly, the function *ttGranier()* converts the voltages from the reference and heat probes into temperatures (Figure 4B). Then, it smooths the time series applying a Savytsky–Golay filter [25] by removing high-frequency components (e.g., electric noise). The function replaces the missing values for the gaps up to 12 h by interpolation. Lately, it estimates the sap flow density for each TreeTalker in a mesh by applying the conversion described by [26], which is assumed to be species independent.

4.4. Under Canopy Radiance

Understanding the spectrum quality of light transmission across the forest canopy can have a significant impact on the design and validation of new forest radiative transfer models. These can be used to better characterize forest–climate interactions or forest production or as a tool to evaluate earth observations [27]. A proper description of the spectral transmittance of forest canopies will enhance our understanding of forest vegetation phenological mechanisms. Each TreeTalker is equipped with two AMS chips (ams-OSRAM AG), the model AS7262 for the visible range and the model AS7263 for the near infra-red range (TT+manual ver. 3.2, September 2020). Each chip can measure six bands. The AS7262 (central wavelengths: 450, 500, 550, 570, 600, 650) has a full width at half maximum (FWHM) of 40 nm, while the with the AS7263 (central wavelengths: 610, 680, 730, 760, 810, 860 nm) has a FWHM of 20nm. The function *ttLight()* makes use of a dedicated data frame created by the *ttScrape()* function. It requires the site coordinates as input arguments, which are used to estimate the sun's position in the sky vault. Firstly, the function smooths the time series for each of the twelve measured spectral bands by applying a Savytsky–Golay filter [25] for removing high-frequency components. Secondly, it filters the spectrometer data according to solar geometry by keeping the measurements acquired with the sun azimuth between $+/-30$ degrees from the local solar noon. Lastly, it aggregates daily values and plots the spectrometer data from a TreeTalkers mesh for a specific band (Figure 4C). The function does not account for the shading effects related to the site topography.

4.5. Relative Humidity and Air Temperature

Forest canopies act as a thermal insulator, cooling the understory when the weather is hot and warming the understory when the weather is cold [28]. These dynamics affect the relative humidity, and these factors act concurrently with the regulation of the ecological processes occurring below the canopy in natural and urban environments [29]. The function *ttRH()* and the function *ttAir()* make use of the data from the thermohygrometer NXP/Freescale, Model: Si7006 (TT+manual ver. 3.2, September 2020). The relative humidity data (Figure 4D) are filtered for a plausibility range, and the gaps up to 12 h are filled by interpolation, while no quality assurance is applied to the temperature data (Figure 5A).

4.6. Tree Stability

Tree stability is an essential characteristic to be monitored because it can provide information about the resilience of aingle trees as well as of the whole forest ecosystem to abiotic disturbances such as windstorms [30,31]. Accelerometers mounted on a tree trunk can record the sway movement of the tree. The tree sway is affected by tree traits such as the mass, wood density, elasticity, and drag coefficient [32] but also by canopy characteristics such as the closure and roughness. Understanding the behavior of this parameter is crucial in forestry for understanding the response to wind, as storm damage can be a large source of economic loss [33]. TreeTalkers measure the trunk movements by a Silicon Labs MMA8451Q 3-Axis Accelerometer equipped with a very low-power, low-profile capacitive MEMS sensor (TT+manual ver. 3.2, September 2020). The *ttStability()* function processes the oscillation of trees due to gravity with a spherical coordinate system. With basic trigonometry, the angle between the gravity vector and the TreeTalker z-axis are assessed by taking in account variations in the angle of tilt in the xy-plane, as described by [34] (Figure 5B). A positive angle means that the corresponding sensor axis is pointed above the relative horizon (referred to in the standard installation settings), whereas a negative angle indicates that the axis is pointed below the relative horizon.

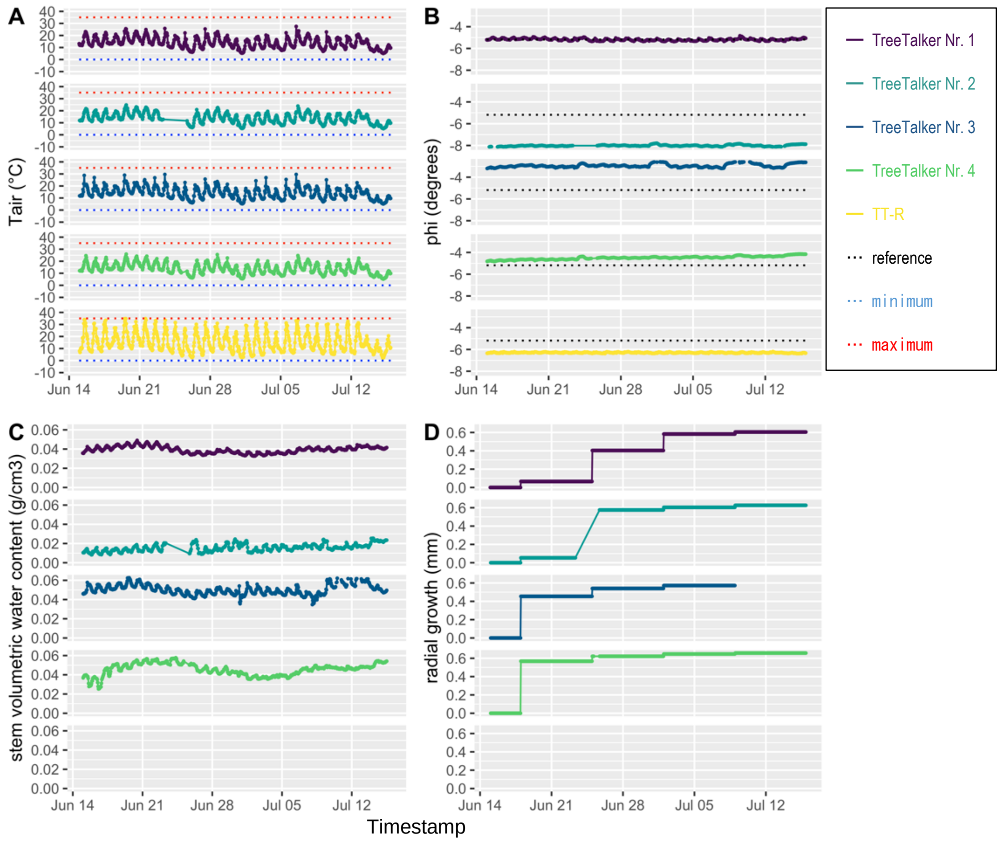

Figure 5. Output of the "ttalkR" plotting utility. (**A**) Air temperature with the reference minimum (dashed blue line) and maximum temperature (dashed red line); (**B**) inclination of the devices; (**C**) stem volumetric content; (**D**) radial growth. The example data refer to four TreeTalkers and a TT-R for the period between 14 June 2021 and 14 July 2021. In (**C**,**D**), the data from the TT-R are missing because it is a reference device outside of the canopy which is not equipped with the corresponding sensors.

4.7. Stem Volumetric Water Content

The water content in trees varies with diel and seasonal cycles, and it is a reservoir for transpiration [35], with sapwood being the most important storage site [36]. Because of the lack of experimental data, the most often-used models for investigating the water balance of vegetated regions do not take into account differences in plant water storage or their influence on the pathways of the transport in the soil–plant–atmosphere system [37]. TreeTalkers make use of a capacitive sensor (MicroPCB) with copper plates (TT+manual ver. 3.2, September 2020) for measuring stem volumetric water content and its dynamics. The method is based on frequency domain measurements and has been demonstrated to be effective for different tree species, but it requires species-specific calibration [38]. The function *ttStWC()* converts the frequency domain measurements into volumetric water content (Figure 5C) by adopting the calibration functions provided by [39]. Because of the necessary temperature dependence correction, we applied a Savytsky–Golay filter [25] to the temperature data in order to remove high-frequency components, and we used a linear interpolation for gaps up to 12 h.

4.8. Radial Growth

The growth of forests is affected by environmental factors [40], and it is a crucial ecophysiological parameter for quantifying the carbon sink of forests [41]. Radial stem growth occurs based on xylem increments on structures already formed, so trees increase in size with age. The function *ttGrowth()* makes use of data frames created by the *ttScrape()* function. It processes the data from GP2Y0A21 Sharp distance sensors. The sensors are deployed as point dendrometers. The distance sensor is positioned at a few centimeters (typically 3 to 4 cm) away from the tree trunk's surface and is kept in place by a carbon fiber stick anchored in the xylem. The function converts the digital numbers into distance (mm) with a second-degree polynomial regression model provided by the producer (TT+manual ver. 3.2, September 2020), and it applies a temporal averaging (median) on a weekly basis in order to remove the signal noise affecting the hourly measurements (Figure 5D).

4.9. Output

Interacting with databases via scripted languages has advantages over querying databases via a graphical user interface. In fact, data manipulations are preserved in the code, and the aggregates, summaries, and other database operations are not lost. As a result, those pre-analysis data manipulation steps are held and can be replicated. The *ttOutput()* function ingests the output from all the previous functions and creates a new database and an associated structure. In addition to the specific measured variables, each table in the database (Table 1) contains references to time and to a unique TreeTalker identifier (ID).

Table 1. Tables and content of the database created by means of the function *ttOutput()*.

Name	Content
df_ttBattery	timestamp, battery voltage, TreeTalker ID
df_ttGranier	timestamp, sap flow density, TreeTalker ID
df_ttLight	date, daily average counts per band, TreeTalker ID
df_ttRH	timestamp, relative humidity, TreeTalker ID
df_ttAir	timestamp, air temperature, TreeTalker ID
df_ttStability	timestamp, Tree stability, TreeTalker ID
df_ttSTtWC	timestamp, Stem volumetric water content, TreeTalker ID
df_ttGrowth	timestamp, Radial growth, TreeTalker ID

We selected the SQLite format because it is self-contained, stand-alone, and the recognized standard for storage and is therefore suitable for making the data accessible to a broad community for further processing and analysis. Additionally, this format is not software-specific, and it provides the benefits of an easy user setup and the absence of the need to configure or manage a server process.

5. Conclusions

In this article, we proposed and demonstrated the ttalkR package as the first step toward a unified TreeTalker data curation and, therefore, as a crucial advancement toward more formal time series analyses and data interpretation. The ttalkR package was first designed as a toolbox for assisting TreeTalker users in MRO activities and for the unified preprocessing of collected data to allow for cross-site analysis. The toolbox was planned as user-friendly and envisages scientists deploying TreeTalkers and pursuing data formatting for research purposes in a standardized but customizable fashion within the R programming language. The ttalkR package provides an approach to TreeTalker data curation by implementing a workflow for a unified conversion from raw numbers to physical units according to the TreeTalker user manual (TT+manual ver. 3.2, September 2020). The concept behind the package is modular, with I/O functions and parameter dedicated functions. We conceived the general package architecture to be adaptable to further hardware developments (i.e., sensor substitution and addition). At the same time, an open code provides possibilities for implementing advanced quality assurance algorithms and new conversion and calibration procedures. Additionally, we adopted a self-contained and stand-alone relational database as the final output format for facilitating data exchange. In the future, the "ttalkR" package can be extended by including the possibility to curate data from older and newer TreeTalker versions. Furthermore, a finer data elaboration level could be added to provide derived indexes and parameters, which will be helpful for forest modelling and the integration with complementary data streams.

In conclusion, our approach provides new opportunities for synthesis analyses based on the TreeTalker data from large-scale networks and their integration with other data streams such as meteorological information and earth observations. Such an approach is a first step for supporting the TreeTalker data life cycle and is suitable for making the collected data accessible. Ultimately, a unified approach for data curation will enable the exploitation of collected information for data-sound model development, the inference of forest attributes, and for addressing novel and broad research questions in macroecology. Yet, a unified processing of TreeTalker data will be the basis for a new environmental cyberinfrastructure across regional and possibly global research networks.

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Data Availability Statement: The code used for this paper and the TreeTalker manual (TT+manual ver. 3.2, September 2020) are freely available at the repository https://github.com/EnricoTomelleri/ttalkR (version 1.0.0) (accessed on 24 April 2022).

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