Climate at ecologically relevant scales: A new temperature and soil moisture logger for long-term microclimate measurement

Jan Wild[a,*], Martin Kopecký[a], Martin Macek[a,b], Martin Šanda[c], Jakub Jankovec[c], Tomáš Haase[d]

[a] Institute of Botany of the Czech Academy of Sciences, Zámek 1, CZ-25243, Průhonice, Czech Republic
[b] Charles University, Faculty of Science, Department of Botany, Benátská 2, CZ-12843, Prague 2, Czech Republic
[c] Department of Irrigation, Drainage and Landscape Engineering, Faculty of Civil Engineering, Czech Technical University in Prague, Thákurova 7, CZ-166 29, Prague 6, Czech Republic
[d] TOMST s.r.o., Michelská 964/78, CZ-141 00, Prague 4, Czech Republic

A B S T R A C T

Climate measurements are needed at a scale at which organisms live and die. Currently available climate sensors, however, are not well suited for long-term field measurements at such a scale. We have therefore developed a new temperature and moisture logger, the Temperature-Moisture-Sensor (TMS), which we designed for a wide range of ecological applications. The device mimics a small herbaceous plant. Its belowground part houses a patented, proprietary soil moisture sensor working on the time-domain transmission principle. Air, surface and soil temperatures are measured simultaneously by three independent sensors. The TMS data logger has a large memory and long battery life, so it is suitable for taking long-term microclimate measurements in the field. With a data acquisition interval of 15 min, it has sufficient memory to last for almost 15 years.

We have thoroughly tested the TMS logger both in the laboratory and in demanding field conditions ranging from tropical rain forests of Africa to high-elevation cold deserts of the Himalayas. The device has provided microclimate measurements in a wide range of environmental conditions and has also performed well in controlled laboratory settings.

The key added value of the TMS logger is that it concurrently measures soil moisture as well as soil, surface and air temperature at a biologically relevant scale. It is also able to continuously measure the microclimate for several years even in the most extreme conditions. The device can therefore be used to build extensive tailored field measurement networks providing crucial data about microclimate conditions shaping biological processes in the face of climate change.

1. Introduction

The climate near the ground – where most terrestrial organisms live – differs from that which is measured by weather stations. This is a long known (Geiger et al., 2009) yet often neglected fact, and thousands of ecological studies use climate data measured using conventional weather stations or data interpolated from these measurements. The climate in which organisms actually live is so different, however, that meteorological data are often ecologically irrelevant (Potter et al., 2013). Fine-scale microclimate measurements are therefore needed to reveal species' ecological requirements (Ashcroft et al., 2009; Gollan et al., 2013; Slavich et al., 2014), especially in the face of ongoing climate change (Scherrer and Körner, 2011; Ashcroft et al., 2012; Franklin et al., 2013).

Obtaining microclimate measurements is not easy, however. First,

numerous loggers are needed to cover microclimate heterogeneity across a landscape (Fridley, 2009; Suggitt et al., 2011; Ashcroft and Gollan, 2012). However, existing professional meteorological loggers are expensive. Researchers therefore use loggers developed for different purposes, for example industrial iButton loggers (Hubbart et al., 2007; Massuel et al., 2009; Suggitt et al., 2011), but large differences in their installation in the field make measurements obtained by them hard to compare. The shielding of loggers from direct sunlight and rain also varies substantially (Tarara and Hoheisel, 2007; Lundquist and Huggett, 2008; Ashcroft and Gollan, 2012; Holden et al., 2013), which makes inter-study comparisons even more difficult (Terando et al., 2017).

Further limitations are related to the construction of loggers or the types of sensors integrated into them. Most available microclimate loggers measure only temperature. However, soil moisture is often a

crucial driver of species' distributions and therefore affects how species respond to climate change (Crimmins et al., 2011; Piedallu et al., 2013). Soil moisture is, however, difficult to measure accurately and currently available loggers are not well suited for continuous long-term field applications (Robinson et al., 2003, 2008). The main reason is that available microclimate loggers often have small data memory and low battery capacity, hampering their long-term deployment needed to capture rare – yet biologically important – extreme events and long-term climate variability (Letten et al., 2013). Microclimate studies are also often faced with frequent disturbance and high failure rates of sensors in the field. For instance, users of the iButton device report up to 27% of lost soil temperature data as a result of failure or disturbance within 6 months of field measurements (MB Ashcroft pers. comm.). Sensor networks established with currently available loggers thus require frequent maintenance, and this hinders the collection of microclimate data in remote regions.

With all these limitations in mind, we have developed and tested a new microclimate data logger called the Temperature-Moisture-Sensor (TMS). It integrates sensors for measuring air, surface and soil temperature as well as soil moisture into a compact unit with a long-lasting battery and large memory capacity. Here we describe the basic concept of the device and the calibration protocol for the proprietary soil moisture sensor, compare measurements acquired using a TMS logger with those recorded by a conventional weather station and examine TMS measurements of soil moisture in soil samples with known water content. We also present examples of the deployment of TMS loggers for long-term microclimate measurements.

2. Methods

2.1. Concept and construction

We designed the TMS data to capture the climatic conditions experienced by a small herbaceous plant (Fig. 1). The device thus resembles a plant 15 cm tall, rooted in the upper soil layer. It bears three temperature sensors positioned at $+15$, 0 and -8 cm relative to the soil surface (further referred to as air, surface and soil temperature). This placement reflects the positions of a plant's leaves, overwintering buds
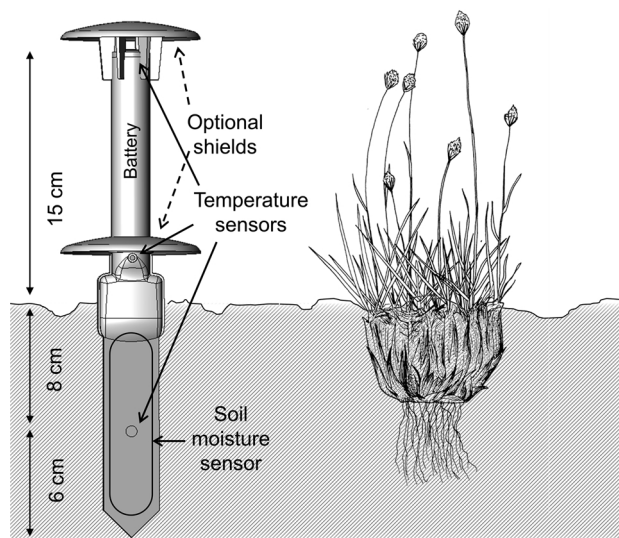
Fig. 1. Scheme of the TMS data logger designed to capture the same climate conditions as a small herbaceous plant. Each TMS device bears three sensors measuring air, surface and soil temperature, and one sensor measuring soil moisture. The TMS logger thus captures temperatures at positions corresponding to plant's leaves, overwintering buds and roots, and measures soil moisture content in its root zone.

and roots (Fig. 1). The bottom part of the TMS logger constitutes a probe measuring volumetric soil moisture to a depth of (approximately) 14 cm. Although we modelled the device on a herbaceous plant, its range of applications is broader. Microlimatic variables measured by the TMS logger are relevant for all organisms living near the ground or in upper soil layers. Moreover, the TMS device measures microclimate variables affecting many ecological processes, including those related to the water and energy balance.

The data logger is constructed of two main parts: The belowground part of the device is built as a multilayer printed circuit board (PCB) from FR4-grade material; this PCB is made using a patented construction process (patent No. CZ304369). The upper part of the PCB houses all electronics and is sealed using a tough but elastic water-resistant epoxy resin (Elan-tech). To further improve mechanical durability, this part is covered by a styrene acrylonitrile (SAN) plastic case. The aboveground part is constructed from a white, mechanically resistant plastic pipe (Speedpex Barrier) and contains the batteries and the thermometer sensors. The uppermost part of the TMS logger is a metal cap which also works as a connector. Data are transferred to a PC using a special adapter connected by a USB cable. At the transfer speed of 250 Kbit, it takes approximately 3 seconds to move data collected over a period of one month (using the default data acquisition interval of 15 min).

2.2. Memory and power supply

With a memory for 524,288 records, the TMS logger collects and stores data over its whole lifetime from the first initialization at the manufacturer. The user is prevented from stopping the collection of data or deleting data from the memory. This prevents data loss due to incorrect user settings. All sensors therefore collect data even during storage. This allows the early detection of malfunctioning loggers and the calibration of consistently inaccurate sensors. Pre-screening and calibration of temperature sensors can significantly improve the accuracy of measurements (Hubbart et al., 2005).

The default and also the longest allowed interval for data collection is 15 min, but different shorter periods can be set. Time is stored in UTC/GMT and is measured using a 32.768-kHz crystal with an accuracy of ± 2 min per month. To prevent clock drift, the time on the data logger is synchronized with that on the connected computer whenever data are downloaded. Each TMS device is powered by a lithium battery (replaceable only by the manufacturer) which should theoretically last for 15 years (using the default data acquisition interval of 15 min).

2.3. Temperature sensors

As temperature sensors, we used the DS7505U+ digital thermometer manufactured by Maxim Integrated (www.maximintegrated.com). This is the same thermometer that is built into the iButton Thermochron series DS192x, which has been used in numerous ecological studies (e.g. Fridley, 2009; Ashcroft et al., 2012; Holden et al., 2016). This thermometer has an absolute resolution of 0.0625 °C over the range from -55 °C to $+125$ °C. The manufacturer declares its accuracy to be ± 0.5 °C in the range between 0 °C and 70 °C. According to our testing and to Hubbart et al. (2005), the thermometer has the same accuracy also below 0 °C. However, users are strongly advised to check each temperature sensor before installation for systematic error or malfunction. Visual inspection of temperature data collected continuously during storage time is very helpful in this case. The air sensor ($+15$ cm) is affixed to the inner part of a metal circular contact, which standardizes the size and shape of the sensor's surface exposed to contact with the air and also serves as a communication interface. Both air and surface sensors are shielded by removable white plastic shields allowing good ventilation but protecting the sensors against direct sunlight (Fig. 1).
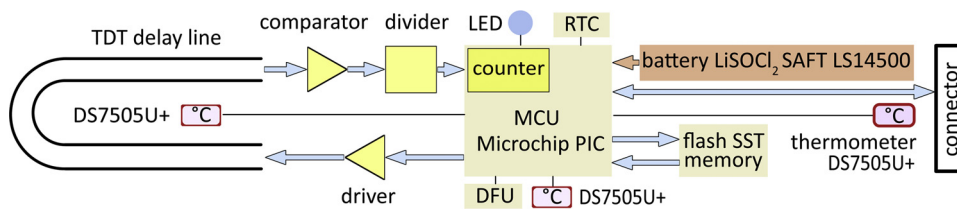
Fig. 2. Schematic diagram of all basic electronic components and their connections inside the TMS data logger. MCU: microcontroller - PIC microchip (eXtreme Low Power); RTC: real-time clock (a separate low power consumption unit with a crystal oscillator); Flash SST: industrial serial flash 32Mbit; DFU: device for upgrade (EEPROM); Thermometer: DS7505U+ (Maxim Integrated) – digital thermometer; LED: optical indicator; TDT delay line: time domain transmission – construction with a PCB (printed circuit board); Connector: communication interface with integrated thermometer (DS7505U+).

2.4. Soil moisture sensor

Various electromagnetic methods based on dielectric permittivity are being used for measuring soil water content in situ. Among them, one of the most frequently used is the time-domain transmission (TDT) method (Robinson et al., 2003, 2008). The time-domain transmission method is also used in the TMS logger to measure volumetric soil moisture with a proprietary, patented sensor (patent No. CZ304153). Briefly, high frequency-shaped electromagnetic pulses (ca 2.5 GHz) are sent through a printed circuit ca 30 cm long (Fig. 2); when a pulse reaches the counting unit, another pulse is sent. This occurs within a 640-microsecond time window. Pulses are counted as a raw moisture signal (50–200 MHz). The number of pulses counted is directly related to the soil moisture content, with higher soil moisture reducing the count of pulses received. The counts are then inverted and scaled to the numerical range of 1–4095 (raw TDT data). Typically recorded values range from 100 (ambient air) to 3500 (distilled water). To transform this relative value into volumetric soil moisture, calibration is needed. In Appendix A, we provide calibration curves for basic soil classes, but for more specific soils or more precise transformation, site-specific calibration should be used. However, the soil moisture sensor is calibrated and tested only for soil water content, and soil moisture measurements from periods with frozen soil should not be used. These periods can be easily detected by the built-in soil temperature sensor.

2.5. Electronic components and assembly

A general scheme showing the assembly of electronic components used in the TMS data logger is presented in Fig. 2. The most important part of the TMS logger is the MCU (PIC microcontroller microchip) running a real-time operating system. All operations are run according to a time schedule, based on a real-time clock.

Each measurement is acquired by the following procedure: When soil moisture is measured, the MCU activates the TDT line through the driver (Fig. 2). A comparator converts the pulses to logical levels (0/1) and a divider changes its high frequency to the speed range of the counter integrated in the MCU. Data are acquired within a certain time frame. During this time the MCU keeps track of the counts and after a given time ascertains the time. When temperature is measured, the data are obtained through the serial bus. All measured data are tracked and saved to the flash memory (Flash SST). Throughout the lifetime of the TMS logger, all measured data are permanently saved to this flash memory. Furthermore, diagnostic data are also saved to the flash memory, making the device a reliable black box.

2.6. Versions

During development, two basic versions of the TMS data logger were intensively tested. These versions, the TMS1 and TMS3/4, have the same temperature sensors and basic design of the soil moisture probe, but they differ in terms of their finish, shielding and firmware (Table 1, Fig. 3a). The more recent versions have improved firmware for soil moisture measurements and increased mechanical durability, but the basic design and sensor placement remain the same and

comparable across versions (see Appendix B). To take full advantage of the soil moisture sensor's unique characteristics, we also constructed different versions intended mainly for hydrological applications, which require completely belowground installation (Fig. 3b).

3. Evaluation of temperature and soil moisture measurements

3.1. Temperature

To illustrate how temperatures measured by the TMS data logger differ from standard meteorological data, we compared temperatures measured by a TMS device with those recorded by an official hydrometeorological station (henceforth referred to as the weather station). Such a comparison cannot be considered an accuracy assessment, because temperatures are measured at different heights and under different instrument settings, but it helps understand how the microclimate near the ground differs from that measured by a conventional weather station.

The measurements were conducted at the weather station of the Czech Hydrometeorological Institute in Průhonice near Prague (50° 0′ 28″ N, 14° 33′ 40″ W, 312 m a.s.l.), equipped with METEOS 5 automatic measuring stations (www.meteoservis.cz/en). We installed a TMS data logger in a short-cut lawn about 3 m from the pole bearing all meteorological sensors. We then compared temperatures logged by the TMS device 15 cm above ground with those recorded by a temperature sensor with a gill-type shield, installed 2 m above ground. In addition, we compared surface temperature data from the middle TMS sensor with data from an unshielded temperature sensor placed on the ground and the data gathered by the belowground TMS sensor with soil temperatures measured 10 cm below the surface. We evaluated differences for both direct measurements taken at 1-h intervals and for daily averages.

Air temperatures recorded 15 cm above ground by the TMS device were more variable than those recorded by the weather station 2 m above ground. The differences in hourly measurements ranged between +8.45 and −6.05 °C (Fig. 4a). Daily means of air temperature from the TMS logger were systematically lower than those obtained by meteorological measurements, but the differences between the two were much smaller than in the case of hourly records (the mean difference being −0.58 °C). These differences are greater in winter and range from −2.02 to 0.6 °C (Fig. 4b). A comparison of temperatures recorded by the surface sensor of the TMS device and by the unshielded ground sensor on the weather station showed the opposite trends. The TMS data logger measures lower temperatures during summer (by as much as 5.08 °C) but similar temperatures during winter (Fig. 4c). Data from the soil sensors differed only marginally (Fig. 4d). The small differences between soil temperatures measured by the TMS logger and the weather station (see also Table 2) suggest that differences between TMS and weather station measurements are not caused by the different temperature sensors, but by the different positions above the ground and by their different shielding.

Interestingly, differences between the TMS logger and the weather station in above ground temperature measurements become even more pronounced when expressed as synthetic climate variables often used in

Table 1
Basic technical characteristics of all versions of the TMS logger developed to date. See Fig. 3 for the different models.

TMS version	TMS1	TMS3	TMS4
Year of production	2009	2011–2013	2017
Design of soil moisture sensor	PCB double layer	PCB multilayer with plastic cover	PCB multilayer with plastic cover
Battery	2 lithium CR 123A	2 lithium CR 123A	1 lithium (Li-SOCl$_2$) LS14500
Data memory	ca 19,200 records	ca 520,000 records	ca 520,000 records
Weight	105 g	117 g	108 g
Connector	TRS connector (6.35 mm audio jack)	Touch-and-hold probe	Touch-and-hold probe
Modifications	Standard	Standard, buriable, USB	Standard, buriable, USB
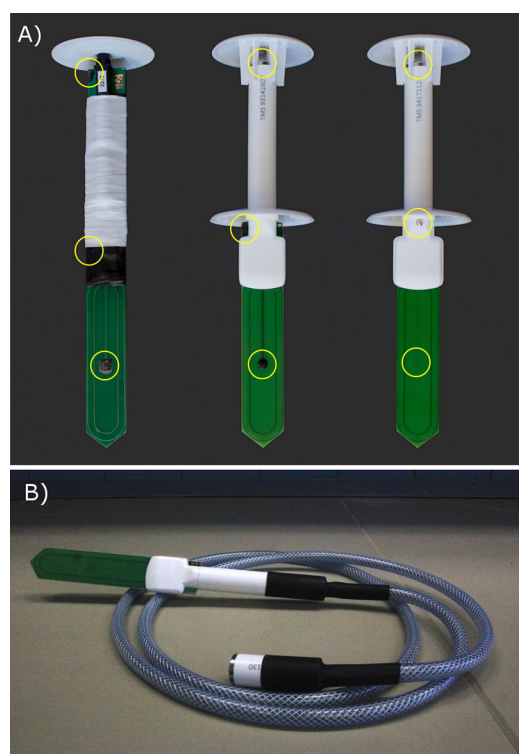
Fig. 3. Comparison of different versions of the TMS device. A) TMS1 (left), TMS3 (middle), TMS4 (right). The positions of temperature sensors are indicated by yellow circles. B) TMS3/4 version adapted for completely below-ground installation, e.g. for hydropedological applications.

ecological studies, for example quantiles of extreme temperatures or cumulative indices such as growing degree days (Table 2). These results suggest that organisms living close to the ground experience quite different microclimates than those measured by weather stations. Researchers studying such organisms should be careful when using data measured by weather stations because actual climate conditions affecting these organisms substantially differ from meteorological measurements, especially when expressed as ecologically important climate extremes and cumulative bioclimate variables.

Because different types of TMS loggers have been produced (Fig. 3) and used to acquire measurements that have already been utilized in several publications (e.g. Dolezal et al., 2016; Dvorský et al., 2017; Řeháková et al., 2017; Moravec et al., 2018), we also compared temperatures measured by different versions of the device. The differences observed are within the accuracy limits stated by the sensor's manufacturer and temperature measurements provided by different versions of the TMS logger are thus fully comparable (see Appendix B, Fig. S6).

3.2. Soil moisture

To validate the relationship between raw TMS measurements and

volumetric soil moisture, and to calibrate raw TMS measurements, we performed laboratory experiments with a wide range of soil classes and tested the sensor for dependence on temperature and salinity (Appendix A). Because the time-domain transition method of soil moisture measurement is sensitive to the contact of the sensor with the soil, we calibrated TMS units in mixed and packed soil samples. First, each soil class sample was mixed, naturally dried and then packed around the sensor in a vessel of defined volume. The weight of the vessel and the raw moisture signal provided by the TMS device were ascertained. Next, we repeated this process, only with a known amount of water added before mixing and packing the soil in the vessel. We repeated this procedure at least four times (but usually 5–7 times) per soil class, with an increasing amount of water in each subsequent step until complete soil saturation. To obtain an estimate of inter-sensor variability of the measurements, we used five TMS devices installed in the vessel.

We found raw TMS measurements to be correlated well with known values of volumetric soil moisture and that the variability among measurements by different TMS units was low (Fig. 5). However, the shape of the relationship between raw TMS measurements and volumetric soil moisture differed between soil classes (Appendix A, Fig. S1). We therefore provide calibration values based on a comparison between raw TMS measurements and volumetric soil moisture data for main soil classes (Appendix A, Table S1).

To further illustrate how the TMS moisture sensor reacts to soil saturation and subsequent drying, we explored the relationship between TMS measurements and daily precipitation data recorded by the weather station. Fig. 6 shows that soil moisture measured by the TMS device increased sharply after substantial rainfall events and then slowly decreased as the soil gradually dried.

4. Applications and limitations

4.1. Field examples

The TMS data logger has already been used in several ecological studies conducted in different climate conditions (Fig. 7). For instance, we used the TMS logger to monitor microclimates in the topographically complex sandstone area of the Bohemian Switzerland National Park in the Czech Republic (Fig. 7a). This lowland region (200–450 m a.s.l.) is home to many plant species otherwise typical for alpine or oceanic regions. These unusual occurrences are traditionally ascribed to the phenomenon of temperature inversion in deep sandstone valleys (Härtel et al., 2013). To verify this assumption, we installed more than 400 TMS units in this region and measured microclimate along topographic gradients from valley bottoms to rock outcrops. Several years of continuous microclimate measurements revealed that valley bottoms were significantly colder during the vegetation season but did not confirm the previously assumed occurrence of cold air pooling (Wild et al., 2013).

We have also tested the TMS device in the extreme climate of the Himalayas (Fig. 7c). In these demanding conditions, TMS loggers were able to operate continuously over the course of several years even above 6000 m a.s.l. (Dvorský et al., 2017). Thanks to the large memory
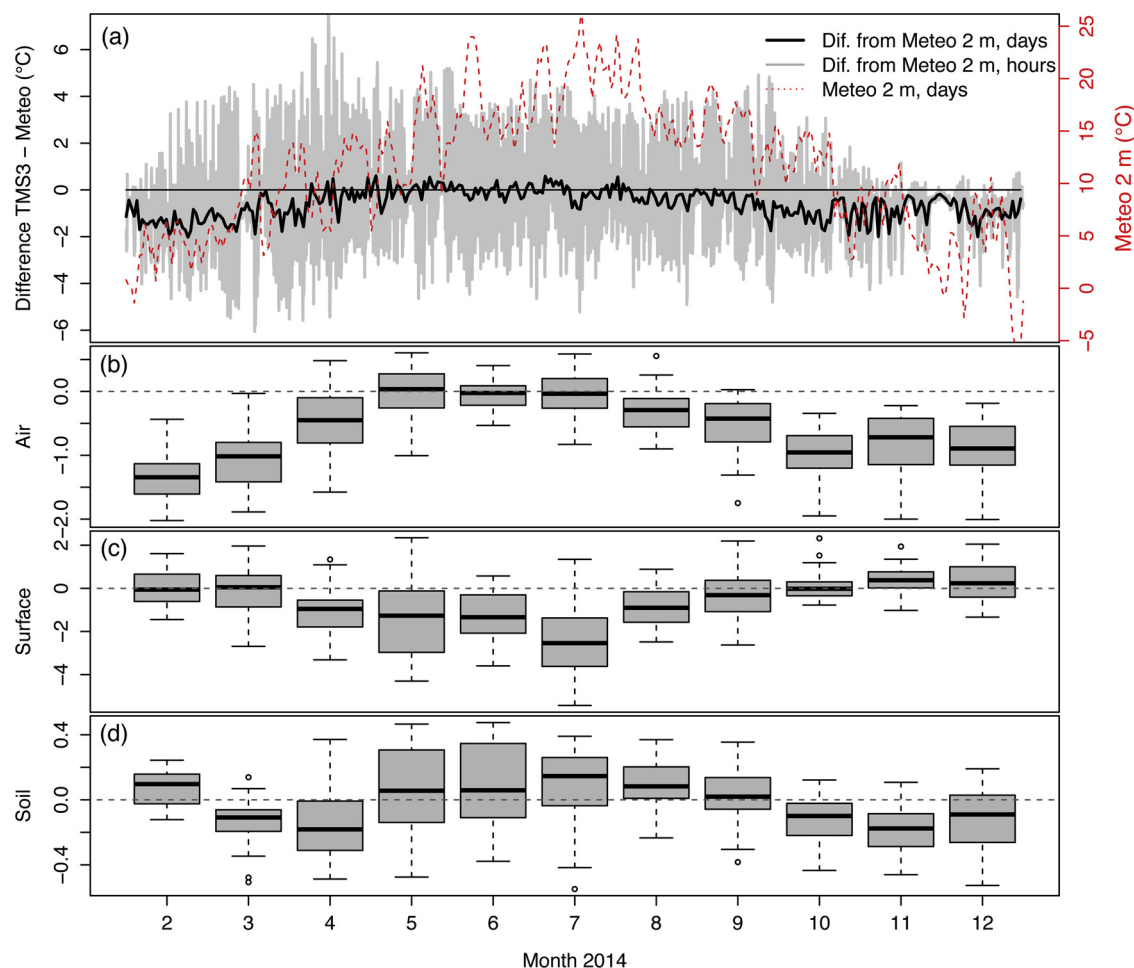
Fig. 4. Differences in temperatures measured with the three temperature sensors of the TMS data logger from temperatures measured by the weather station. (a) – TMS air temperature, daily (black line) and hourly (grey line) differences and daily average temperatures from the weather station (dashed red line, 'Meteo'). (b, c, d) – differences summarized over individual months (note the two different scales of the y-axis). The entire measurement period was without permanent snow cover. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

Table 2

Comparison of climate variables measured by the TMS logger and by the weather station (Wstation). Values of the climate variables were calculated from 15 min measurements obtained over 11 months without snow cover. T_{mean}– average temperature; $T_{max}95$ – 95th percentile of daily maxima; $T_{min}5$ – 5th percentile of daily minima; GDD_{10} – growing degree days (sum of daily mean temperatures exceeding 10 °C); GDH_{10} – growing degree hours (sum of daily temperatures exceeding 10 °C, calculated as the daily average of temperatures over the base temperature for each hour, divided by 24). Max daily range – maximum daily range.

Climate variable	Air		Surface		Soil	
	TMS	Wstation	TMS	Wstation	TMS	Wstation
T_{mean}	10.86	11.65	11.43	12.28	11.35	11.45
$T_{max}95$	32.04	29.6	32.59	44.94	21	20.3
$T_{min}5$	−5.32	−2.94	−2.13	−7.14	2	2
GDD_{10}	1105.6	1170.1	1295.3	1537.7	1014.8	1009.6
GDH_{10}	1270.6	1258.7	1375.8	1793	1019.4	1019.4
Max daily range	26	20.8	23.13	42.9	5.1	3.4

and long battery life of TMS loggers, we were able to ascertain detailed microclimate characteristics of sites with the highest growing vascular plants on Earth (Angel et al., 2016), where average daily air temperatures remain below zero for more than 300 days of the year, daily minima often fall below −30 °C, and the lowest temperature reached was −43 °C. Moreover, simultaneous soil and air temperature
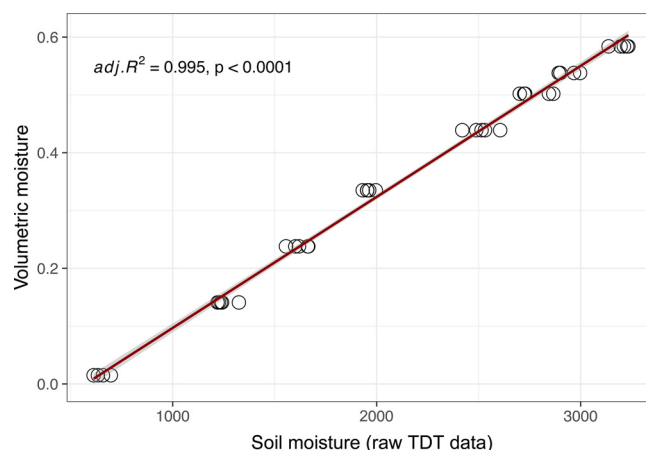
Fig. 5. Relationship between raw signal provided by TMS data loggers and laboratory-determined volumetric moisture content for the sandy loam soil class. Points represent individual measurements by five different TMS devices and the line represents the linear relationship fitted to these data. The grey band surrounding the regression line represents the 95% pointwise confidence interval.

measurements provided evidence that soil, not air, temperatures are crucial for plant survival in these extreme conditions (Dvorský et al., 2016; Dolezal et al., 2016).
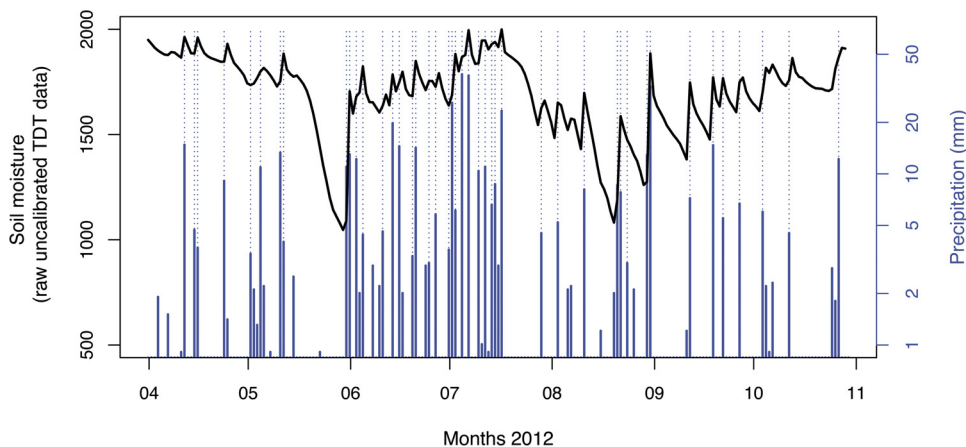
Fig. 6. Daily mean soil moisture measured by the TMS data logger compared to daily precipitation measured by the weather station. Values of daily precipitation (blue bars) are logarithmically transformed and TMS measurements (black line) represent raw uncalibrated data. Where daily precipitation exceeded 3 mm, the bar is extended with a thin dotted line for better comparability with measured soil moisture. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

Currently we are using TMS loggers to monitor forest understorey microclimates (Fig. 7b). The effect of tree cover on the below-canopy climate is indisputable but rarely quantified. Although air temperatures are being recorded systematically across the globe, temperature data from forest understoreys are scarce because weather stations are placed outside forests (De Frenne and Verheyen, 2016). Nevertheless, existing data indicate high variability of below-canopy microclimates due to reduced mixing of air near the ground and high variability in canopy structure. It has even been speculated that canopy cover can substantially buffer the effect of climate change (De Frenne et al., 2013). However, direct quantification of the relationship between canopy characteristics and the below-canopy climate is needed to support this hypothesis. The TMS data loggers are ideal for such a purpose because they measure the climate near the ground, where most organisms live, which allows to directly relate microclimate variability and biodiversity.

4.2. Limitations

The great variability of conditions across the case studies and the large number of TMS devices tested allowed us to explore the limitations of the data logger. We learned that openly installed TMS loggers are often damaged by wild animals such as deer, wild boar and bear. For example, within a 6-month measuring period in Central European forests, up to 66% of TMS loggers were pulled out of the ground by wild animals, which caused 15% of loggers installed in the field to malfunction. We therefore recommend to protect the devices against large animals, for example with wire cages (Fig. 8). The use of such protection reduced the rate of disturbance by animals to a mere two percent over six months. Beside mechanical disturbance by animals, we experienced TMS4 logger malfunctions due to technical reasons in only one percent of cases during the first six months after installation.

The entire belowground part of every TMS logger must be in direct contact with the soil to accurately measure soil moisture. This is usually achieved by forcing the device directly into the soil. In stony soils, however, The PCB board can be deeply scratched, which can cause the moisture sensor to malfunction. In stony soils, we therefore recommend to first penetrate the substrate using a metal plate or to dig a larger hole, install the TMS logger and then backfill the hole with soil. Although the second approach disrupts the soil structure, it provides better contact between the soil and the sensor. In shrinking and swelling soil (e.g. in drying clay soils), loss of contact between the sensor and the soil may result in lower than actual soil moisture values.

5. Conclusion

Although the term 'microclimate' has long been a part of every ecologist's vocabulary, its importance is not reflected in the development of technical equipment to measure it. Existing data loggers are either too expensive, or have only limited memory and battery capacity, which prevents long-term and simultaneously large-scale microclimate measurements. However, such measurements have the potential to improve the estimation of the climate niches of many organism, and by extension, their response to the ongoing climate change (Lenoir et al., 2017; Slavich et al., 2014). Collecting longer term in-situ data will also help to establish the potential for microclimate heterogeneity to buffer species against local extinctions by the creation of climate microrefugia (Suggitt et al., 2018).

For these reasons, we have developed the TMS data logger, which can provide reliable long-term data on air and soil temperature as well as on soil moisture in a wide range of field conditions. Thanks to its small size, the TMS device directly measures the microclimate experienced by organisms living near the ground, and when properly installed, the TMS logger also fixes the positions of sensors relative to the soil surface and therefore provides measurements that are standardized across studies. The TMS data logger is also able to gather microclimate data for years without any care or maintenance, which facilitates long-term measurements in remote regions and across vast areas. This makes the TMS the ideal data logger for monitoring ecologically relevant microclimates across different spatial scales and habitat types.

Declarations of interest

The technical development of the TMS was led by T. Haase of TOMST Ltd., the company which owns two Czech patents for solutions used in the manufacture of the device and which also manufactures and sells it commercially (see www.tomst.com for current prices and the availability of data loggers). It is only in the case of T. Haase from TOMST Ltd that there therefore exists a potential conflict of interest in connection with this article presenting findings made using TMS loggers. We declare that although T. Haase participated in the technical development of the TMS, he did not participate in the collection of data, their analyses or their interpretation presented in this article. Before the manuscript was sent for review, its accuracy as regards technical details was checked by T. Haase as the co-author with expertise in the field of electronics.

The remaining co-authors have no conflict of interest. They are not and have not been reimbursed by TOMST Ltd., be it directly or through benefits. Neither they nor any of their relatives are members of any company bodies or have any financial interest in the sales of TMS units.

Authors' contributions

JW led the field testing and writing of the manuscript. MK and MM tested the units and contributed critically to their design and functionality. MS and JJ co-developed and tested the soil moisture sensor,
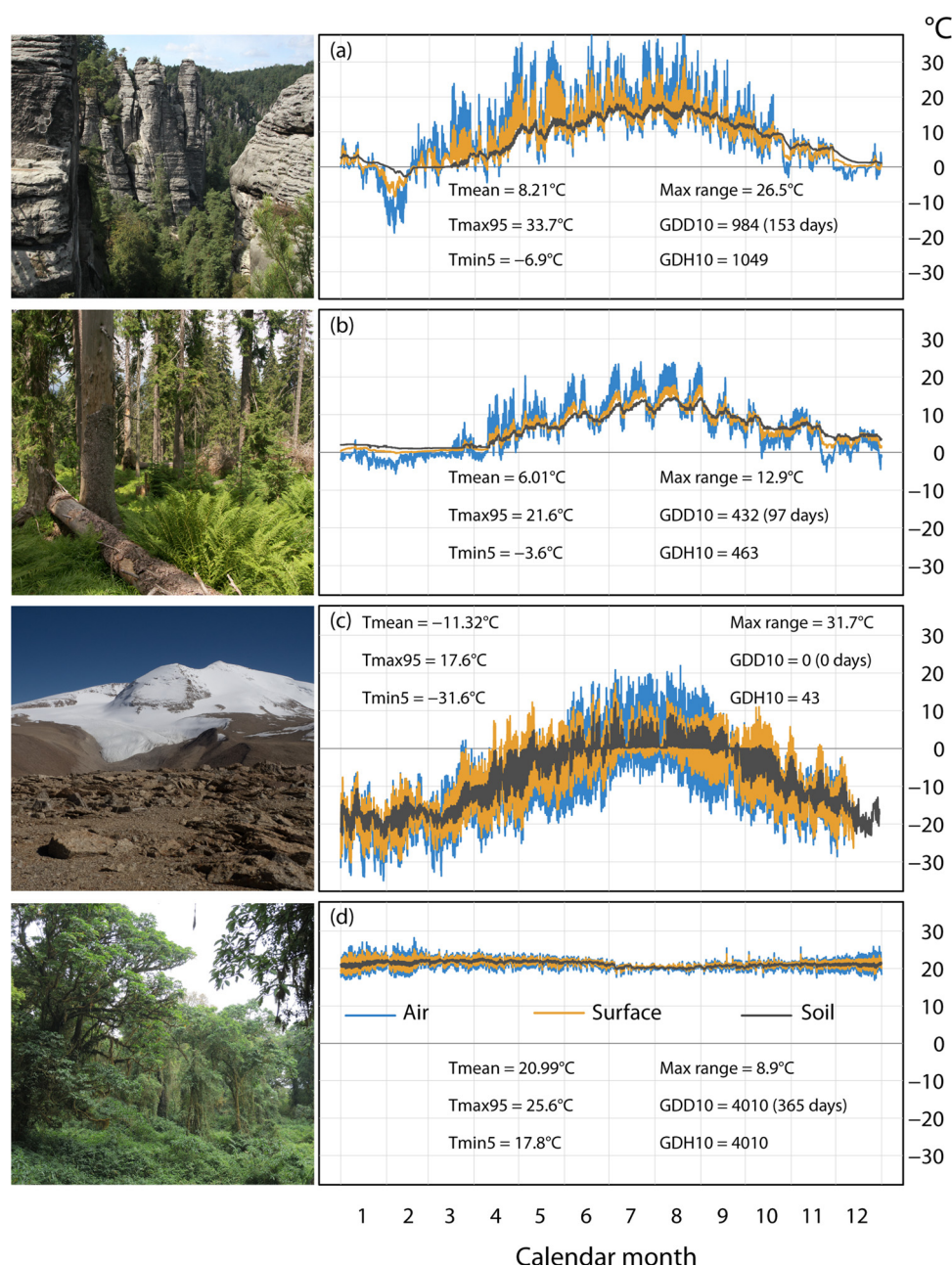
Fig. 7. Example of yearly climate profiles measured by the TMS device in four contrasting environments: (a) exposed sandstone rock outcrop, 450 m a.s.l., Bohemian Switzerland National Park, Czech Republic; (b) coniferous mountain spruce forest, 950 m a.s.l., Bohemian forest, Czech Republic; (c) upper limit of vascular plant life, 6150 m a.s.l., Ladakh, India; (d) tropical rain forest, 650 m a.s.l., Mt. Cameroon, Cameroon, photo J. Doležal. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

Fig. 8. TMS data logger protected by a wire cage (30 × 30 × 50 cm) affixed in the soil by 20 cm long steel rods. In our experience, this mechanical defence successfully prevents damage by wild boar and deer.

and TH led the technical development. All authors contributed significantly to drafts of this paper and gave their final approval for its publication.

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Appendices A and B

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