









Continuous quantification of forest microclimate temperatures in space and time using fibre-optic technology

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Abstract

1. Most species experience microclimate temperatures, that is, variable and fine-grained thermal conditions determined by atmospheric conditions interacting with biotic and abiotic components of the earth's surface. Unfortunately, measuring microclimates at biologically meaningful grain sizes is challenging.
2. We showcase the potential of fibre-optic distributed temperature sensing (DTS) to quantify diurnal variation in microclimatic air temperatures during the growing season along a 135-m forest edge-to-interior transect at 25-cm horizontal resolution. We benchmark DTS measurements against the microclimate quantified with ultrafine wire thermocouples and more conventional sensors at 15-m intervals along the transect.
3. Diurnal measurements from DTS indicate maximal cooling of forest floor temperatures (up to -6°C) in the morning (around 8:00 AM) and well away from the forest edge. Negative offset values gradually increased during the day reaching zero (0°C) in the evening (around 21:00 PM).
4. *Synthesis.* While both DTS and discrete point sampling with microclimate loggers allow to quantify diurnal cycles of microclimate gradients with unified spatial and temporal patterns, DTS provides accurate temperature measurements at a spatial detail nearly impossible to achieve with discrete point sampling. When applied over transects of several hundreds of meters—up to kilometres—fibre-optic DTS is a cost-efficient alternative offering substantial potential to advancing microclimate research.

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KEYWORDS

distributed temperature sensing, diurnal variation, forest microclimate, optical fibre, remote sensing, temperature data logger, temperature offset

1 | INTRODUCTION

Air temperatures are conventionally measured by synoptic weather stations following the World Meteorological Organization's guidelines. These guidelines dictate that sensors should be installed in open fields at 1.5–2 m height above short grass and well away from trees and buildings (World Meteorological Organization, 2008). However, these so-called “macroclimatic” conditions generally do not represent the thermal conditions that are experienced by organisms living near the ground surface (Box 1), and drive ecosystem processes. Most terrestrial species respond to microclimate temperatures: highly variable (in space) thermal conditions determined by the joint action of macroclimate, local weather conditions, and landscape-scale determinants such as (micro-)topography and vegetation structure (Aalto et al., 2022; De Lombaerde et al., 2022; Zellweger et al., 2019). Whereas macroclimate warming is a strong indicator of temperature fluctuations over longer time scales and across large spatial extents, it is the change in microclimate temperatures at the much finer spatial extents (e.g. within forest stands—down to meter resolution) that are most relevant to people (Gillerot et al., 2022) and nature (Maclean & Early, 2023; Sanczuk et al., 2023).

Measuring microclimate air temperatures, however, is challenging (Maclean et al., 2021). First, microclimates are fine-grained, with thermal differences up to several degrees celsius (°C) observed at grain sizes of 0.1–10 m² (Figure 1). Particularly at ecotones such as boundary zones between forests and cities, or in areas with particular topographic heterogeneity such as in alpine and arctic ecosystems, clines in microclimatic temperatures can be especially pronounced (Aalto et al., 2022; De Pauw et al., 2023; Meeussen et al., 2021). Monitoring such gradients requires an appropriate sampling design (e.g. De Pauw et al., 2023; Meeussen et al., 2021; Vanneste et al., 2020). High-resolution grid sampling, for example, allows one to quantify the spatial heterogeneity in microclimatic conditions accurately, but inherently demands an enormous amount of sensors to meet the spatial detail relevant to biodiversity (Niittynen et al., 2020). Finally, as a result of direct sunlight on conventional microclimate loggers, sensor heating due to energy fluxes is a severe issue that pitfalls measuring temperatures accurately (Maclean et al., 2021). Covering temperature sensors with radiation shields only partially solves this problem and cannot prevent upward bias of absolute temperature measurements under sunny conditions. The implementation of industrial fibre-optic-based monitoring technology that allows measuring temperature in a temporal and spatial quasi-continuous manner has a large potential to revolutionise microclimate research.

We present a novel means of performing a quasi-continuous quantification of microclimatic temperatures in space (at 25-cm

BOX 1 The forest microclimate and its relevance for biodiversity

Organisms living within or below tree canopies in forests experience microclimatic conditions very different from the macroclimate, with buffered daily and yearly oscillations in temperature and humidity as a direct consequence of shading and evapotranspiration of trees (Figure 1). On average, understorey maximum temperatures are 4.1°C cooler compared to free-air measurements (i.e. the temperature offset) (De Frenne et al., 2019). In structurally complex forests with a closed canopy, maximum temperatures can deviate up to 8.3°C during warm summer days (Meeussen et al., 2021). The capacity of forest canopies to buffer forest floor temperature fluctuations is, however, highly heterogeneous in space and time, and inherently linked to forest structural complexity, forest density and distance to the forest edge (Figure 1). Simple-structured forests and forest edges typically have less buffered microclimates (De Frenne et al., 2019; Meeussen et al., 2021).

The magnitude of thermal buffering in forests is a critical habitat feature for understorey species, determining their survival, growth and fecundity (Sanczuk et al., 2023). In addition, the amount of light coming through the forest canopy is a strong driver of the understorey community composition and structure (Elemans, 2004). Finally, forest microclimates often cause understorey species to experience warming temperatures that substantially differ from the temperature increase measured in open fields (Zellweger et al., 2020). As a result of climate warming, canopy opening and elevated light levels can accelerate thermophilisation rates in understorey communities (De Frenne et al., 2015; Govaert et al., 2021). Exactly these microclimate temperatures and light levels vary at very small spatiotemporal resolution (Figure 1c,d), making it indispensable to quantify this heterogeneity.

resolution) and over time (at 1-min resolution) using fibre-optic distributed temperature sensing (DTS), and benchmark these measurements against a complementary set of two different microclimate data loggers (Table 1). DTS allows measuring temperatures quasi-continuously at an unprecedented spatial resolution that is nearly impossible to obtain from point sampling with more conventional data logger-type temperature sensors or weather stations (from a logistical and financial point of view, Table 1). Technically, DTS records

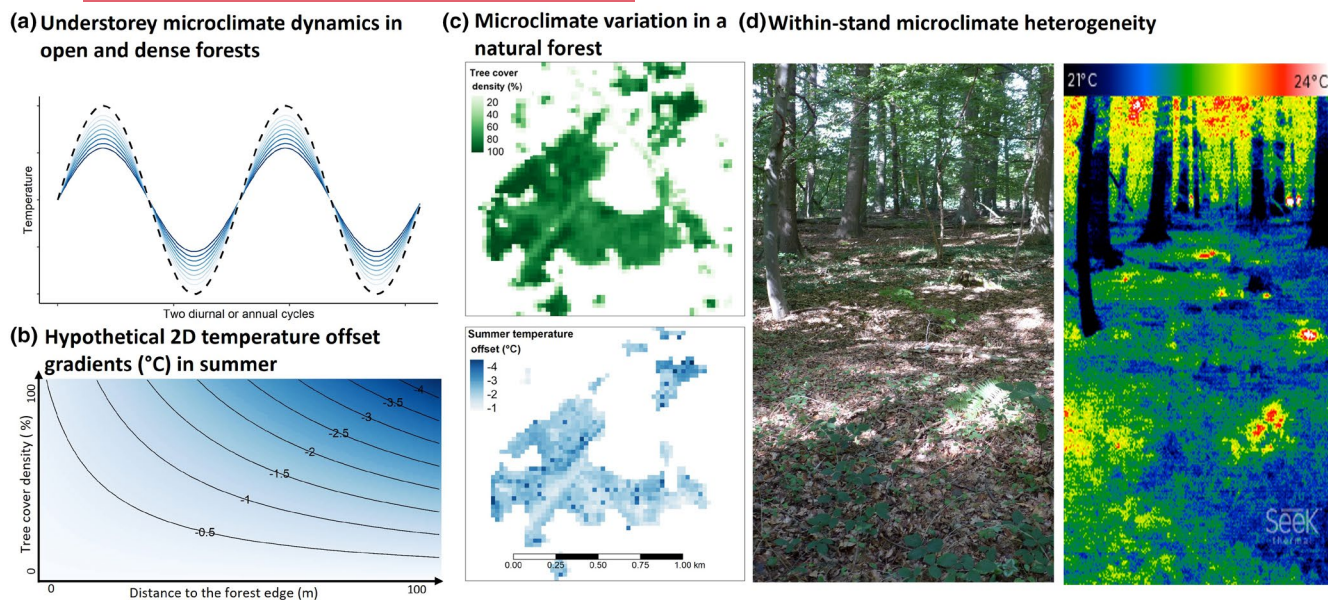


FIGURE 1 Examples of microclimate gradients in temperate forests. (a) Hypothetical variation in temperature over two diurnal or annual climate cycles in open field conditions (black dashed line) and understory microclimate temperatures in more open (pale blue lines, indicating less buffering) to dense (dark blue lines, indicating more buffering) forests. (b) Hypothetical two-dimensional gradients in summer temperature offset values (microclimate minus macroclimate temperature; °C) driven by the distance to the forest edge and tree cover density. (c) An empirical example of the variation in tree cover density (%) and summer temperature offset values (°C) in the Aelmoeseneie forest (Belgium). Tree cover density data were derived from Hansen et al. (2013), temperature offset values were derived Haesen et al. (2021), and represent the mean for the months of June, July and August. (d) Microclimate heterogeneity within a beech forest in August 2022 in Belgium. Images of the same view were taken with a regular camera (left) and an infrared camera (right). ©Pieter Sanczuk.

temperatures along an optical fibre as a continuous profile based on the Optical Time-Domain Reflectometry (OTDR) analysis of the spontaneous Raman (Shatarah & Olbrycht, 2017). In this technique, the DTS sends a short light pulse through the optical fibre and collects the corresponding backscattered light, which mainly comprises the Rayleigh, Raman and Brillouin components. The amplitude of the anti-stokes components of the Raman backscattering is sensitive to the temperature of the fibre, and this parameter can be used to extract the geolocated local temperature of the fibre in DTS systems. Geolocation (i.e. the distance along the optic fibre) is based on variation in the arrival time of the backscattered light. Although the high spatial-resolution monitoring of thermal environmental conditions using DTS is not new [e.g. frequently applied in industrial contexts (Ukil et al., 2012)], applications to quantify microclimate temperature regimes in ecosystems remain surprisingly rare (Krause et al., 2013; Schilperoord et al., 2022; Tyler et al., 2008; Voosen, 2024). The deployment of DTS in microclimate sciences can deliver invaluable data since time series of in situ ultrafine-grained temperature measurements are frequently identified as a key missing data type for the next-generation microclimate models (De Frenne et al., 2021; Lembrechts & Lenoir, 2020).

DTS technology was applied along a forest edge-to-interior transect during a time period of ca. 2 months (54 days) within the growing season (June–July) of 2023. Specifically, we measured air temperatures at 1 m height above the forest floor along a 135-m gradient using fibre-optic DTS (Figure 2). We benchmarked the DTS measurements against a complementary set of two different microclimate data loggers

located at 15-m intervals along the full transect (see Table 1). We installed high-end ultrafine wire thermocouples and more conventional microclimate data loggers for benchmarking.

2 | METHODS

2.1 | Study site and experimental setup

The study was performed in a ca. 30 ha old-growth mixed deciduous forest in Gontrode, Belgium (50°58'30" N, 3°48'16" E, 16 m a.s.l.). The forest is dominated by ash (*Fraxinus excelsior* L.), pedunculate oak (*Quercus robur* L.), beech (*Fagus sylvatica* L.), and sycamore maple (*Acer pseudoplatanus* L.). European rowan (*Sorbus aucuparia* L.), European hazelnut (*Corylus avellana* L.) and alder buckthorn (*Frangula alnus* Mill.) dominate the shrub layer. Due to ash dieback in the most recent years, large canopy gaps are occurring within the forest stand (Figure 2). A 135-m straight transect was established from the forest edge (0 m) to the forest interior (135 m), with the first part (0–75 m) being denser and dominated by pedunculate oak and beech compared to the last part (75–135 m) which is dominated by ash and maple. The transect crosses a small brook (at ca. 90 m) though topographic variation is otherwise limited. At 3-m intervals, wooden poles were installed to mount the optical fibre, and at 10 locations additional data loggers (see further) were installed at 15-m intervals starting from the forest edge (Figure 2).

TABLE 1 Overview of the different microclimate sensors used in this study, the technical specifications and the estimated cost for quasi-continuous sampling with each of the sensor types.

Data type and unit	Sensor type	Make and model	Technical specs	Min. sampling interval	Pros and cons	Implemented sampling interval in this study	Estimated cost for quasi-continuous sampling of a 135-m transect
Temperature (°C), quasi-continuous measurements	Distributed temperature sensing: DTS N45-Series (model type: AP Sensing N4586A-R02-C02) https://www.apsen-sing.com/technolog/dts-n45-series	Orange PVC-coated 0.9 mm diameter optical fibre connected to AP sensing DTS N45-series read-out unit and standard desktop for data storage	Accuracy of temperature measurements (−40°C to +85°C) = ±0.1°C	Temporal interval: 10s Spatial interval: 0.25 ± 0.5 m	+ Ultra-high spatial resolution + High thermal accuracy + Potentially avoids shielding issues (remains to be calibrated) − Prone to environmental disturbance − Needs continuous power supply − Difficult to operate remotely	Spatial sampling interval: 0.25 m Temporal sampling interval: 10s and stored as 1-min aggregates Sampling at 1 m height	Depending on the exact configuration, the typical cost of a short-range DTS system is in the range of 25–40 K Euros
Temperature (°C), point measurements	Thermocouple 0.076 mm K-type (nickel chromium/nickel aluminium) ultrafine wire thermocouple with exposed welded junction with acrylic conformal coating. Sensor is prewired to SurveyTag logger	SurveyTag MC-01 battery powered data logger with high-speed burst averaging using the Maxim MAX31856 precision thermocouple chip. Data recovery via USB https://surveytag.co.uk/ Loggers are calibrated by the developer	Powered from a single replaceable AA battery Ultrafine wire thermocouple prewired to logger Accuracy of logger (−20°C to +85°C) = ±0.83°C Accuracy of K-type thermocouple (−40°C to +260°C) ± 2.5°C Combined accuracy (−20°C to +85°C) ± 3.33°C without calibration Operating temperature of logger −20°C to +50°C Logger can be insulated for more extreme conditions	Designed to activate periodically (minimum 10s) and store single averaged temperature reading derived from a high-speed burst of up to 64 readings (burst can be over 30 readings a second, depending on sample settings)	+ Less sensitive to radiative fluxes + Minimises issues caused by turbulence-induced rapid fluctuations in air temperature + Avoids shielding issues + Easy to operate remotely − Still in development phase	Spatial sampling interval: 15 m Temporal sampling interval: 60min Sampling at 1 m height	€54,000 (ca. €100 per sensor × 4 sensors per meter × 135 m transect length)
Temperature (°C), point measurements	TMS4 https://tomstom.com/web/en/systems/tms-tms-4/	TOMST, Prague, Czech Republic	Resolution: 0.0625°C Operating range: −40°C to +60°C	60s	+ Conventional logger type + Easy to operate remotely + Three temperate sensors at vertical ground surface distance of +0.15 m, +0.02 m and −0.06 m − Bias due to radiative fluxes on white radiation shield	Spatial sampling interval: 15 m Temporal sampling interval: 15min Sampling at 0.15 m height	€51,840 (€96 per sensor × 4 sensors per meter × 135 m transect length)

TABLE 1 (Continued)

Data type and unit	Sensor type	Make and model	Technical specs	Min. sampling interval	Pros and cons	Implemented sampling interval in this study	Estimated cost for quasi-continuous sampling of a 135-m transect
PAR ($\mu\text{mol m}^{-2} \text{ s}^{-1}$) and temperature, point measurements	Xtreem Photosynthetic Active Radiation Logger http://lodyseydat arecording.com/	Odyssey	Operating range: Cosine-corrected photosynthetic irradiance between 400 and 700nm	60s	+ Easy to operate remotely + Data read-out via Bluetooth + Measures temperature and PAR - Saturated measurements if sampling interval too long - Needs calibration for absolute values	Spatial sampling interval: 15m Temporal sampling interval: 5 min Sampling at 1 m height	€164,700 (€305 per sensor \times 4 sensors per meter \times 135 m transect length)

[Correction added on 6 November 2025 after first online publication: The text in the last column of the first row has been updated].

2.2 | Microclimate air temperature and light data

Microclimate temperatures were measured in a quasi-continuous manner using fibre-optic DTS. We benchmarked the DTS measurements against a complementary set of two different microclimate data loggers located at 15-m intervals along the full transect (see [Table 1](#)). We installed ultrafine wire thermocouples and more conventional microclimate data loggers as a control. Light regimes were quantified through photosynthetic active radiation (PAR) loggers.

2.2.1 | DTS of microclimate

During a time period of 54 days in the growing season (1 June 2023–24 July 2023), we measured air temperatures at 1 m height along a 135-m forest edge-to-interior gradient with fibre-optic DTS. Temperatures were measured with a thin single-ended optical fibre of 0.9 mm diameter covered by an orange PVC coating. The optical fibre was connected to a DTS N45-Series read-out unit (model type: AP Sensing N4586A-R02-C02; <https://www.apsensing.com/technology/dts-n45-series>), allowing us to measure temperatures at a spatial resolution of 25 cm and at a temporal interval of 10 s. The DTS device was connected to a standard desktop computer to store 1-min-aggregated raw output data daily on an 8 GB SD card. Because local disturbances such as sharp fibre bends can cause biased temperature measurements, also data on signal loss is recorded continuously in space (at 25-cm resolution) and time (every 10 s, but data are stored at 1 min aggregated averages). Signal loss is measured in decibel reduction per meter and should ideally decrease linearly along the fibre length. Signal loss is typically presented in so-called loss curves, showing decibel reduction (dB) as a function of fibre length (dB/m). Local disturbances of the fibre induce more-than-average signal loss which can be deduced from these loss curves. Raw data files (so-called 'tra-file') were converted into raw CSV files using the software program AP Sensing N45 Utility 2.0 provided by the hardware developer. Raw CSV files (containing temperature data at spatial intervals of 25 cm along the full fibre length at 1-min-aggregated measurements) were further processed in R 4.0 (R Core Team, 2021). We further aggregated the data into hourly averages (to meet the temporal resolution of the synoptic weather station data; see further) at the 25-cm resolution and merged the data into one data frame for downstream analyses and plotting. R scripts to process, merge and plot raw data files (CSV format) extracted from DTS are available from Sanczuk et al. (2025). The scripts use the R packages *dplyr*, *ggplot2* and *raster* (Hijmans & Van Etten, 2012).

2.2.2 | Ultrafine wire microclimate monitoring

Ultrafine wire thermocouples (SurveyTag loggers; <https://surveytag.co.uk/>; a prior calibrated by the developer) designed for obtaining atmospheric temperature fluctuations with the highest accuracy were attached to each of 10 wooden poles at 1 m above the soil surface.

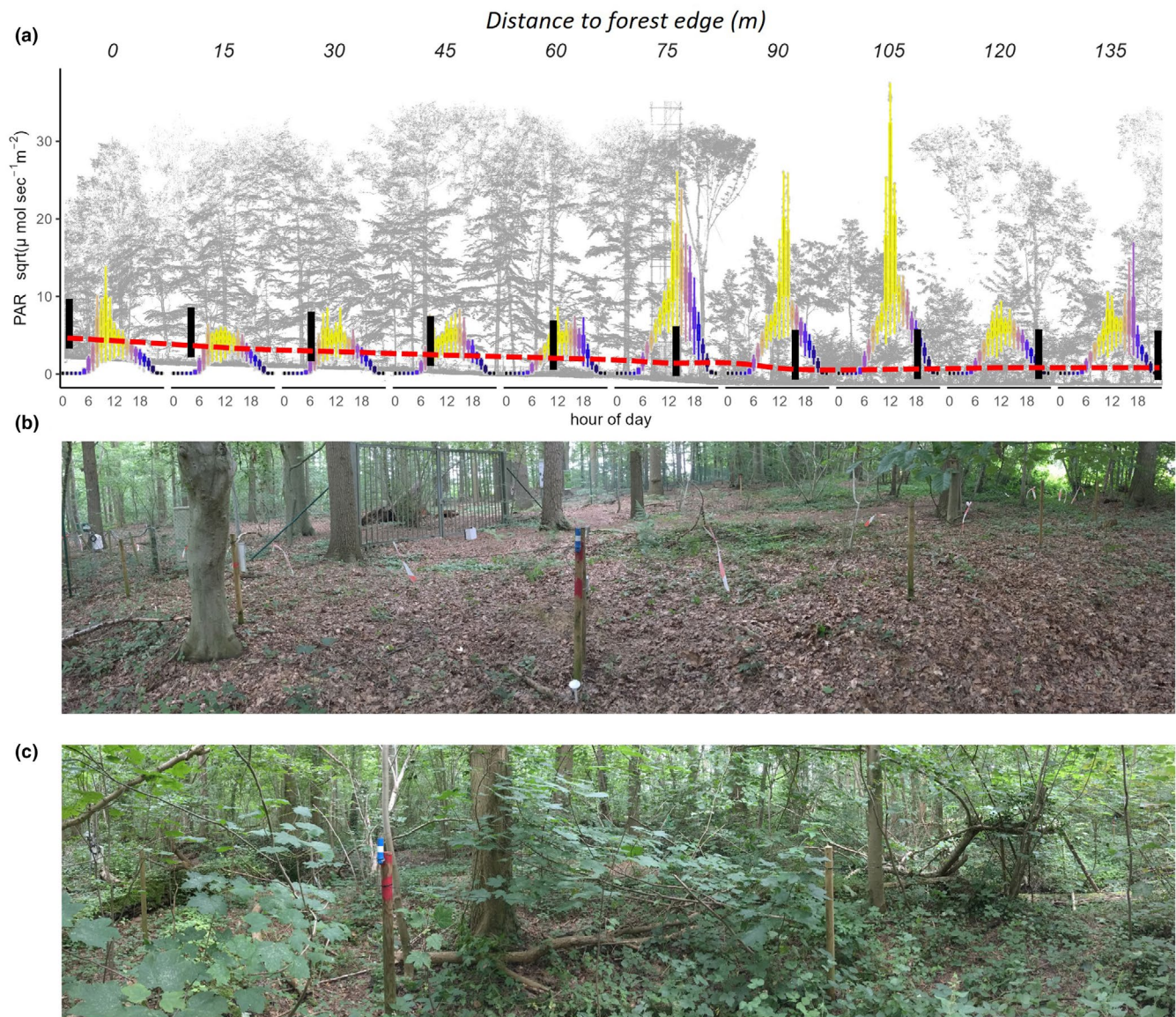


FIGURE 2 Sampling design and visual representation of the study site based on mid-growing season terrestrial laser scanning data. (a) Point cloud of the 135-m forest transect, derived from mid-growing season (10th of July) terrestrial laser scanning with a RIEGL VZ400i, starting from the forest edge (0m) to the forest interior (135m). See [Methods S1](#) for details. Along the full transect, a thin optical fibre (here schematically indicated in red) was installed at 1-m height above the forest floor for distributed temperature sensing at 25-cm spatial resolution. At 15-m intervals ($n=10$, blue bars in figure), two different temperature data loggers and photosynthetic active radiation (PAR) sensors were installed. Diurnal cycles of PAR levels are plotted as boxplots, representing the variation in PAR for each hour of the day, with the brightest and darkest colours denoting noon and midnight, respectively. Discrete 15-m intervals are displayed in the facets. (b) Typical vegetation structure of the first part of the forest structure (0–75 m; picture taken at 15 m from the forest edge), being dense and dominated by pedunculate oak and beach. (c) Typical vegetation structure of the last part (75–135 m, picture taken at 105 m from the forest edge) of the forest transect, which is a more open overstorey and is dominated by ash and maple. In all picture, the exact track of the optical fibre is highlighted with a white dotted line. The blue data loggers at 1-m height are Odyssey PAR sensors. The white data loggers on the forest floor are TMS4 microclimate sensors. ©Pieter Sanczuk.

The SurveyTag loggers avoid the issue of direct solar radiation heating the sensors as they remain highly thermally coupled to surrounding air due to ultrafine-wire thermocouples. They take rapid burst measurements of temperature and store averages of these measurements to circumvent issues caused by fluctuating temperatures in turbulent air (Maclean et al., 2021). These rapid burst measurements were recorded at hourly intervals.

2.2.3 | Conventional microclimate data loggers

In situ microclimate temperatures were measured at 15 cm above the soil surface with conventional loggers [type: TMS4 loggers from TOMST (Wild et al., 2019)]. This type of logger is the most often used logger type in SoilTemp, a comprehensive global database of near-surface temperatures (Lembrechts et al., 2021).

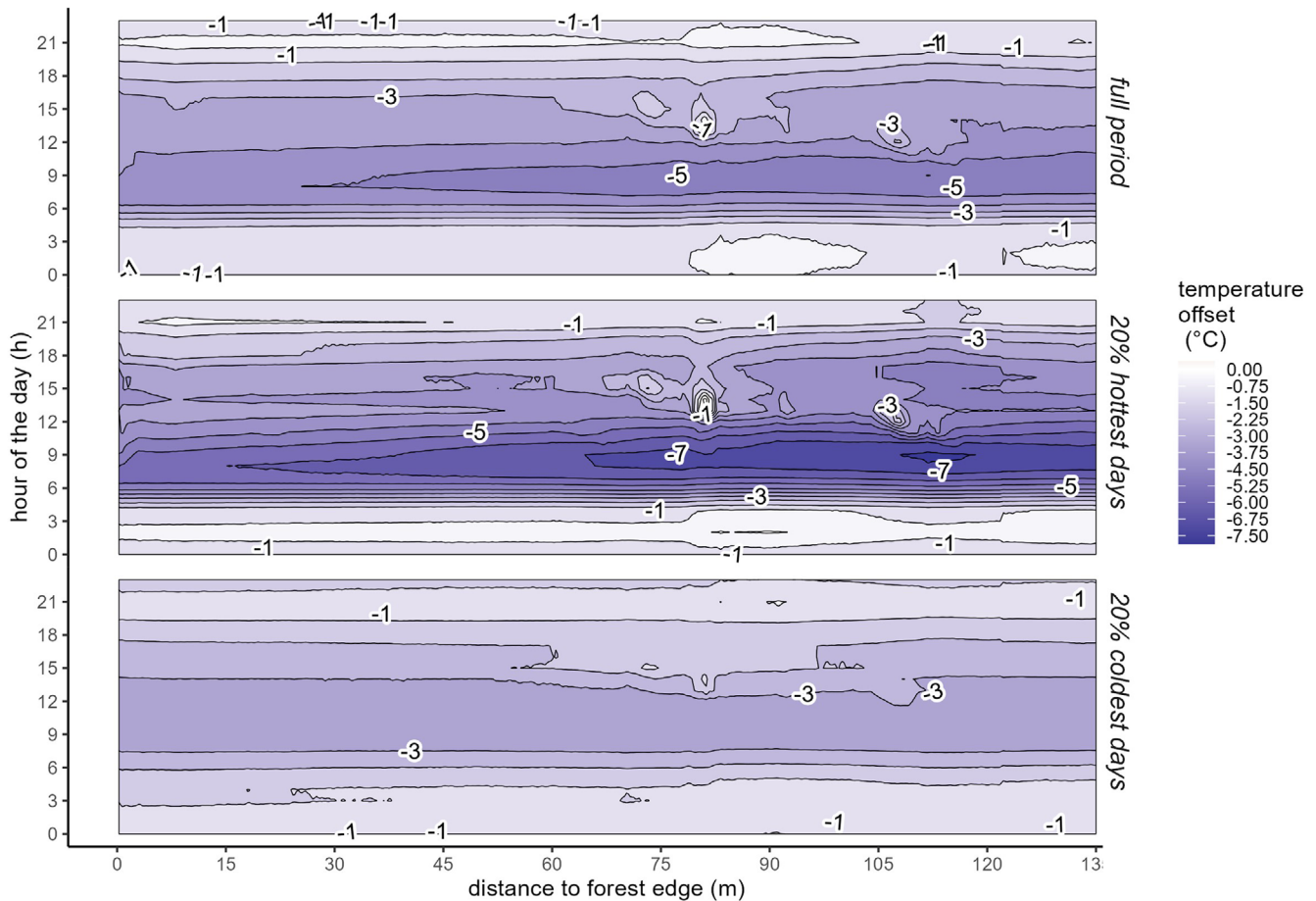


FIGURE 3 Diurnal gradients of temperature offset values along the forest edge-to-interior gradient derived from DTS. Plotted are average offset values across the entire study period (top), and the average offset values for the 20% hottest (central) and the 20% coldest days (bottom). Microclimatic temperatures were expressed relative to synoptic weather station measurements (temperature offset values; calculated as forest temperatures minus weather station temperatures). Negative values indicate cooler conditions within the forest compared to open field conditions. In all plots, more intense colours indicate more negative offset values. Lines represent isolines of equal offset.

Sensors of air temperatures were covered by a white radiation shield. The TMS4 loggers were installed 15 cm south-oriented from each wooden pole along the transect ($n=10$). Local air temperatures were recorded at 15-min intervals from 1 June 2023 until 23 August 2023. TMS4 temperature measurements were aggregated into hourly mean values.

2.2.4 | Photosynthetic active radiation (PAR)

Levels of photosynthetically active radiation (PAR) below the tree canopy were quantified with Odyssey photosynthetically active radiation (unit: $\mu\text{mol m}^{-2} \text{s}^{-1}$) data loggers at 15-m intervals at 1-m height. The PAR loggers collected data at 5-min intervals. The data were aggregated into hourly mean values for plotting. Levels of growing season PAR varied strongly along the transect and were the lowest at 15 m from the forest edge (location dominated by mature beech and oak trees; average daily maximum PAR: $26.3 \mu\text{mol m}^{-2} \text{s}^{-1}$) and the highest at 105 m (plot location with high impact of

natural disturbance due to ash dieback; average daily maximum PAR: $555.0 \mu\text{mol m}^{-2} \text{s}^{-1}$).

2.3 | Quantifying temperature offset values

All microclimate temperature data (from DTS, SurveyTag and TMS4 sensors) were contrasted against synoptic weather station data (i.e. the macroclimate) obtained at hourly resolution from the nearest official synoptic weather station installed in Merelbeke-Melle (Belgium: $50^{\circ}58'49.3'' \text{N}$; $3^{\circ}48'57.4'' \text{E}$) and maintained by the Royal Meteorological Institute (RMI) of Belgium (996-m horizontal distance to the study site, in an open grassland). We quantified the magnitude of temperature offset by subtracting hourly averaged microclimate from macroclimate temperature data. The offset values represent the magnitude of thermal cooling experienced by species living below tree canopies, with more negative offset values indicating a higher cooling (i.e. cooler within the forest compared to open field conditions). Plotting and analyses were performed on

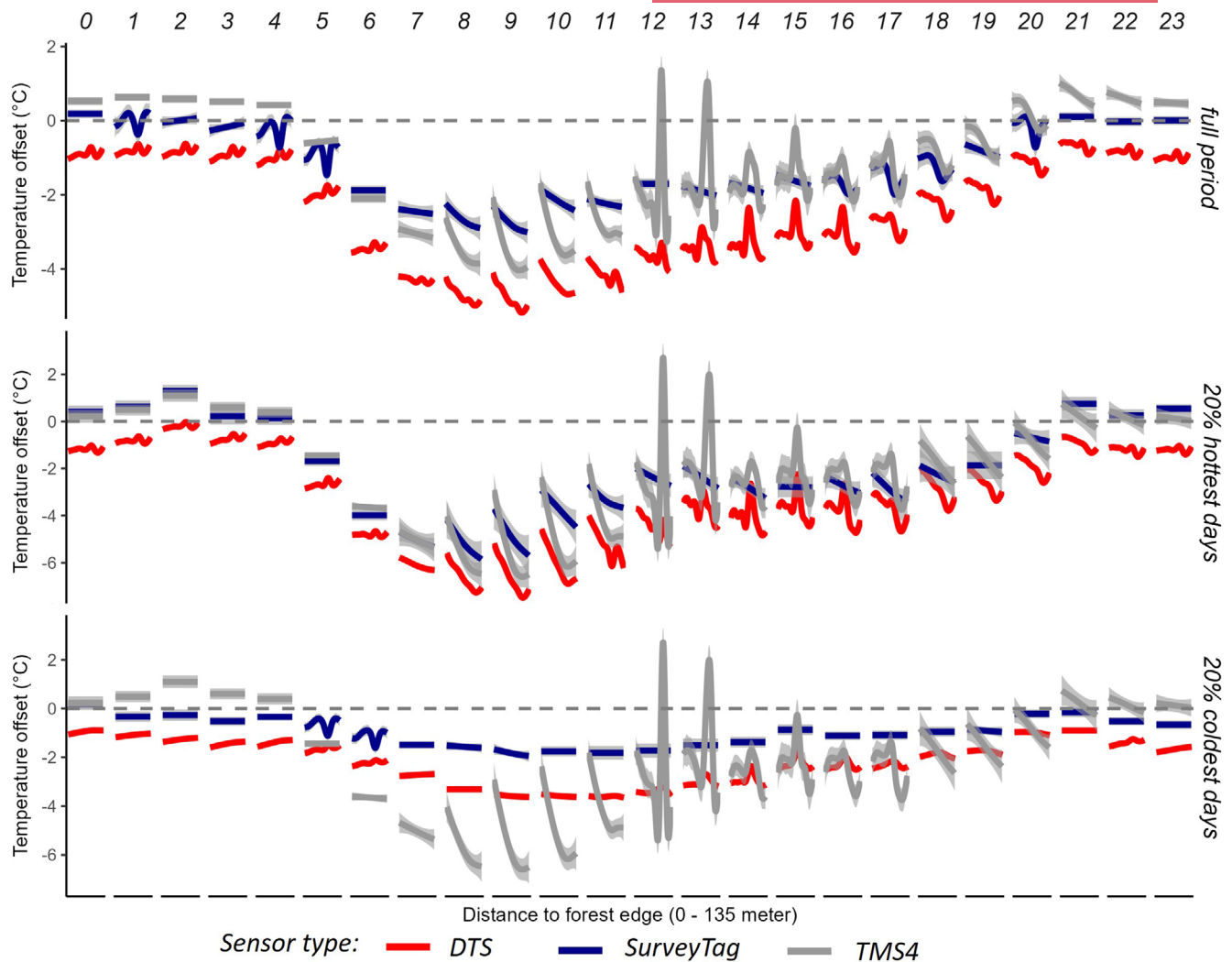


FIGURE 4 Diurnal gradients in microclimate edge-to-interior gradients along a 135-m-long transect quantified with three different sensor types. Lines represent model fit of a generalised additive model fitted to temperature data from distributed temperature sensing (DTS; red) which quantifies microclimate temperatures at 25-cm spatial resolution, and ultrafine wire microclimate data loggers (SurveyTag; blue) and conventional TMS4 microclimate loggers (grey) installed at 15-m intervals. Hours of the day (0–23 h) are displayed in the facets. Microclimatic temperatures were expressed relative to synoptic weather station measurements (temperature offset values; calculated as forest temperatures minus weather station temperatures). Negative values indicate cooler conditions within the forest compared to open field conditions.

data from the full study period, and a subset of the 20% hottest days (i.e. daily maximum synoptic temperatures $\geq 26.44^{\circ}\text{C}$, n days = 17) and the 20% coldest days (i.e. daily maximum synoptic temperatures $\leq 20.22^{\circ}\text{C}$, n days = 18).

3 | RESULTS AND DISCUSSION

3.1 | Diurnal microclimate edge-to-interior gradients inferred from DTS

Spatial gradients in forest microclimate varied strongly between day and night-time (Figures 3 and 4). On average, the lowest cooling effect brought about by forest canopies was observed during nights (highest temperature offset close to 0°C within the time

period 9:00 PM–4:00 AM), whereas maximal cooling was monitored in the morning around 8:00 AM (most negative offset values up to -6°C). This is remarkable since the more negative offset values are generally expected at the hottest moment of the day (here, in the afternoon between 3:00 and 4:00 PM; Figure S1) (Meeussen et al., 2021). Since the coldest macroclimatic temperatures were generally measured between 3:00 and 4:00 AM, we expect these negative offsets to result from thermal inertia brought about by the local environmental conditions that are very different from open field conditions due to, for instance, larger volumes of aboveground biomass, more humid air- and soil conditions, and lower wind speed below tree canopies—which together determine the forest microclimatic conditions. In addition, also the optical path length through the foliage per unit leaf area is typically much longer in the morning when the sun is low above the horizon in

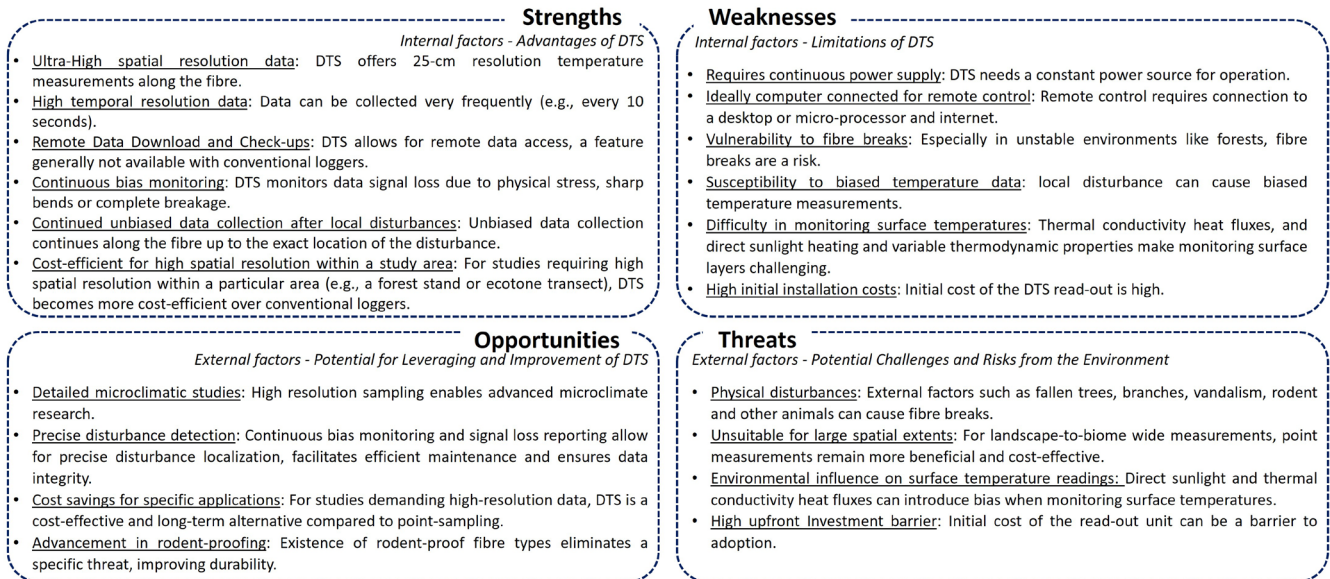


FIGURE 5 Summarising SWOT (Strengths, Weaknesses, Opportunities, Threats) analysis of the use of fibre-optic distributed temperature sensing (DTS) in field conditions. Properties related to the application of DTS in field conditions are listed and structured following a SWOT framework. Strengths and Weaknesses were identified as advantages and limitations that are inherent to DTS (hence, internal factors). Opportunities and threats were identified as the potential and challenges in an applied context (hence, external factors).

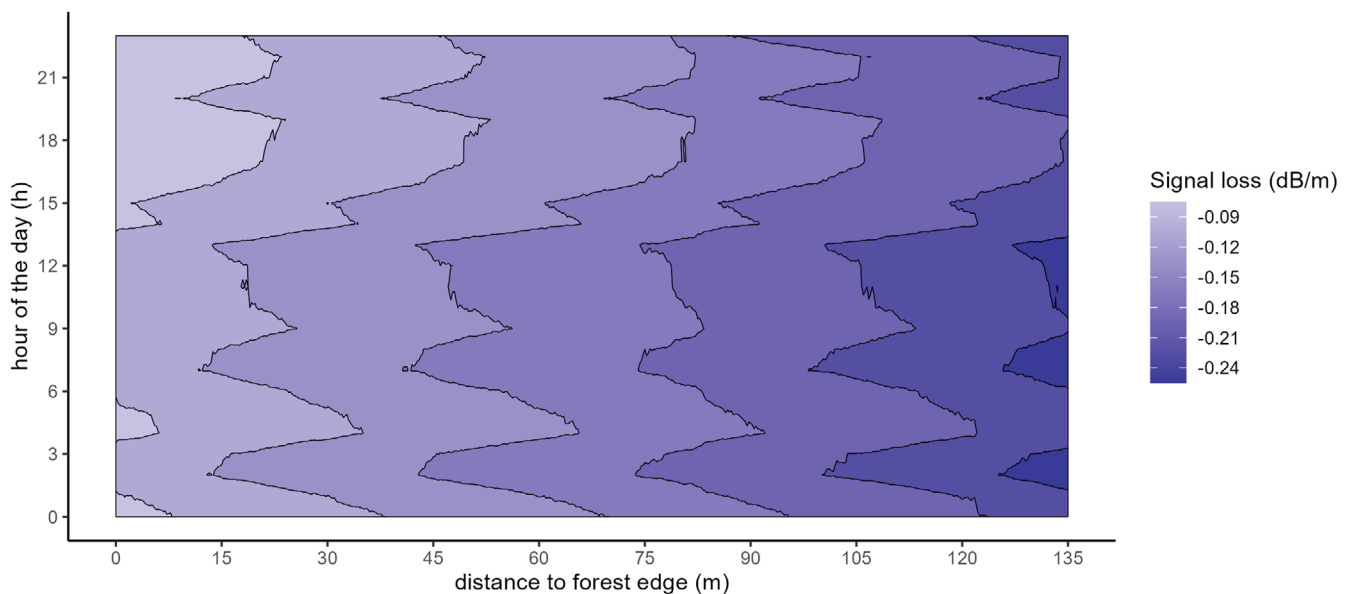


FIGURE 6 'Bias monitoring' as the average data signal loss over the whole study period along the fibre. Signal loss is measured in decibel reduction per meter (dB/m). Unbiased temperature records along the full fibre length are linked to signal loss curves that decrease linearly in space. Sharp fibre bends that cause biased temperature measurements induce more-than-average signal loss and thus biased temperature measurements at the stress location (example presented in Figure S2).

contrast to midday radiation, which attenuates solar radiation more in morning hours than at noon.

Temporal clines in the offset were most clear between 4:00 and 8:00AM. Offset values gradually increased from 8:00AM until they reached zero (0°C) in the evening around 21:00PM. This pattern was most pronounced during the hottest days. Temporal variation in offset values was limited during night-time (21:00PM–4:00AM).

Surprisingly, edge-to-interior gradients were rather subtle, and most clearly visible during the hottest days, while such gradients were almost absent during the coldest days of the growing season. The impacts of structural variation in the overstorey layer did not clearly affect thermal conditions during night-time and morning. However, reduced canopy cover around 85m from the forest edge due to severe Ash dieback (Figure 1) strongly reduced the thermal

cooling effect in the afternoon during the hottest period of the day (12:00–16:00PM). This indicates that canopy gaps, even if only small in size (e.g. <30-m diameter), disturb forests' buffering capacity of thermal extremes—which in turn can amplify warming responses in understorey biodiversity.

3.2 | DTS versus ultrafine wire and conventional microclimate loggers

Absolute differences in temperature offset measurements varied with sensor type and hour of the day, possibly brought about by direct solar radiation impacting each sensor type differently (e.g. owing to variation in the sensor surface area, mass or colour). Benchmarking the temperature records from the DTS with conventional microclimate sensors (TMS4) and high-end ultrafine wire thermocouples (SurveyTag) indicated that data recorded with the DTS more closely matched measurements from the SurveyTag loggers (root mean square error [RMSE]=1.23) than the TMS4 loggers (RMSE=1.41). SurveyTag data loggers have been shown to be more accurate in various environmental conditions, and particularly in open habitats, compared to TMS4 loggers (Maclean et al., 2021), providing us support to the thermal accuracy of DTS. Spatial patterns in microclimate offset values inferred from continuous (in space) microclimate measurements with DTS provided a level of detail impossible to obtain from point sampling with microclimate data loggers (Figure 4). Such time series data of in situ ultrafine-grained temperature measurements constitute a key missing data type for the next-generation microclimate models (De Frenne et al., 2021; Lembrechts & Lenoir, 2020) and may contribute to the development of dynamic vegetation and species distribution models at unprecedented accuracy. Nonetheless, discrete point sampling with data loggers has proven to yield valuable data for calibrating microclimate models (De Lombaerde et al., 2022; Haesen et al., 2021), in particular when spatial sampling designs are adopted to assumed gradients at ecotones. Spatial sampling can also be optimised using appropriate algorithms (Lembrechts et al., 2021). Discrete logger-type measurements, however, generally do not provide data on thermal gradients at very fine grain sizes (e.g. <1 m, but mostly much finer; see empirical example in Figure 1d). This is nevertheless crucial for biodiversity, in particular for areas remarkably spatial variation in growing conditions (e.g. due to extreme variable topography typical in arctic ecosystems or overstorey structure in forests) (Niittynen et al., 2020; Sanczuk et al., 2023), or for the prediction of microrefugia required for many species to cope unfavourable macroclimate conditions (Lenoir et al., 2017).

As a result of direct sunlight on microclimate data loggers, sensor heating due to energy fluxes are a severe issue that pitfalls measuring temperatures accurately (Maclean et al., 2021), even though sensors are covered with radiation shields. This was exemplified by the positive offset values recorded during the hottest days with conventional microclimate loggers (type: TMS4) covered by white

radiation shields (microclimate offset values of ca. +2.5°C were recorded around 12:00AM, which typically results from direct sunlight on the radiation shield). Ultrafine-wire thermocouples, in contrast, have the advantage over the conventional TMS4 sensors as they promise to obtain more accurate measurements of microclimatic air temperatures in sunny conditions as the temperatures of the sensor remain closely coupled to surrounding air temperatures (Maclean et al., 2021), and our results confirm this. Energy fluxes causing biased temperature measurements with DTS appear minimal in our data (as measurements were more comparable to ultrafine wire thermocouples). Still, its accuracy in the open (with direct solar radiation on the optical fibre) versus more hidden environmental conditions remains to be quantified. Subtle differences between DTS and SurveyTag temperature measurements, however, do exist for various reasons, which are among others variation in the degree of sunlight radiation captured, optical properties of sensor surface material and sensor mass. This should be a scope of further research.

3.3 | When (not) to use DTS?

In a SWOT (Strengths, Weaknesses, Opportunities, Threats) framework, we summarised the advantages and limitations inherent to DTS, as well as its potential and challenges for an applied context (Figure 5). Several challenges but also multiple opportunities arise with DTS which makes its application (not) ideal to use in field conditions:

- Compared to most conventional microclimate loggers, DTS requires a continuous power supply for operation and is ideally connected to a computer for remote control. On the other hand, remote data download and check-ups are possible with DTS, which is generally not (yet) the case for conventional microclimate loggers (but see Pieters et al., 2021).
- Fibre breaks can occur due to disturbances (e.g. fallen trees and branches, vandalism or rodents; note that rodent-proof fibre types with aramid coating do exist and effectively rule out rodent damage). Also, sharp bends or physical stress on the fibre may induce biased temperature data. 'Bias monitoring' is performed continuously by the DTS stored along with the temperature records. Signal loss indeed decreased linearly along the fibre length (Figure 6), indicating unbiased temperature measurements.
- Monitoring thermal conditions of surface layers such as the soil surface or tree trunk thermal conditions is difficult, mainly due to thermal conductivity heat fluxes between the optical fibre and the surface layer, but also as a result from heating due to energy fluxes by direct sunlight on the surface layer itself. Both types of energy fluxes strongly depend on physical parameters of the contact layer, and an a priori evaluation of the thermodynamic properties of the focal contact layer should ideally take place (e.g. in laboratory conditions). Monitoring surface temperatures is typically difficult with conventional logger-type

microclimate sensors. Alternatives such as thermal (infrared) cameras (Figure 1d) are available that accurately monitor surface temperatures but these are often difficult to deploy continuously in field conditions.

- Mainly due to the initial cost of the read-out unit required for DTS, installation costs are high relative to the spatial extent that can be sampled. Yet, if very high spatial resolution measurements of microclimatic temperature conditions are aimed for within one particular study area (e.g. a forest stand or a single transect along an ecotone gradient), DTS may quickly become a cost-efficient alternative to the installation of several conventional microclimate loggers (e.g. after initial purchase of the read-out unit, microclimate data can be collected at the installation cost of ca. €3.8-per meter not including the price of the read-out unit; Table 1). On the contrary, in the situation the microclimatic temperature conditions are aimed to be quantified over a larger spatial extent (e.g. with a particular landscape, to biome-wide measurement), logger-type sensors (point measurements) are evidently more beneficial.

3.4 | An outlook for optical-fibre technology in microclimate research

Numerous lines of research in global change biology may take advantage of optical-fibre DTS. For instance, the impacts of differently shaped and sized forest canopy gaps on temperature offset values are often less understood (Kovács et al., 2020), despite increasing relevance for sustainable forestry (Sanczuk et al., 2023). Equipping forest floors with DTS in a spatial raster design is feasible across relatively large areas (e.g. up to several hectares) since optical fibres allow quasi-continuous measurements of temperature along fibre lengths up to 30km (Voosen, 2024) and is therefore also a cost-efficient way to microclimate data collection (Table 1). Spatial raster designs may be combined with high-resolution gridded environmental data extracted from last-generation remote sensing data sources such as airborne LiDAR data, Sentinel-1 or Sentinel-2 data to link microclimatic temperatures to biotic variables (e.g. tree species composition and biomass), topographic heterogeneity (e.g. effect of slope and aspect), water bodies (e.g. effects of ponds and rivers) or roads (Chen et al., 2022). Furthermore, DTS may advance our understanding of microclimatic variation at otherwise hard-to-reach locations. For instance, in forests, vertical gradients from the forest floor to above the canopy have been rarely quantified (Schilperoort et al., 2022), despite their importance for within-canopy living species such as exotherms (e.g. activity/density of insects such as bark beetles), bats and birds. Also in mountainous regions, DTS may provide the unique opportunity to collect temperature data on cliffs, steep ravines, fine-grained soil surface depressions or in karst landscapes. Finally, in marine habitats, DTS may be used to quantify microclimates within complex coral environments or kelp forests which harbour a vast number of species that most likely experience

environmental conditions that are very different from the open marine habitat (Voosen, 2024). Such gradients could relatively easily be quantified with fibre-optic technology, and this measuring method becomes quickly very cost-efficient if quasi-continuous sampling is aimed over longer distances (i.e. >100m). In sum, DTS opens exciting novel opportunities in microclimate research across virtually all ecosystems.

AUTHOR CONTRIBUTIONS

Pieter Sanczuk, Kim Calders, Hans Verbeeck and Pieter De Frenne conceived the concept and ideas. Pieter Sanczuk and Zhizhi Yang installed the experiment. Pieter Sanczuk, Louise Terryn, Tom E. Verhelst and Ruth Warfield collected field data. Pieter Sanczuk performed the data analyses and wrote the initial draft of the manuscript, with major contributions from Pieter De Frenne. All authors provided input on each section and critically revised the final version of the manuscript. All authors gave approval for the publication of this version.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interests.


PEER REVIEW

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DATA AVAILABILITY STATEMENT

Raw data and R code related to this manuscript are available via <https://doi.org/10.6084/m9.figshare.27094462.v1> (Sanczuk et al., 2025).

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

Figure S1. Variation in synoptic weather station temperatures during the study period. The coldest temperatures were observed between 3:00 and 4:00 AM. Hottest temperatures were observed between 15:00 and 16:00 PM. The colour gradient represents the hours of the day, with the brightest and darkest colours reprinting noon and midnight, respectively.

Figure S2. The effect of more-than-average data signal loss on recorded temperatures due to a sharp bend in the fibre. Signal loss is measured in decibel reduction per meter (dB/m). Unbiased temperature records along the full fibre length are linked to signal loss curves that decrease linearly in space (red curves, recorded at 12 AM on 20 July 2023). Sharp fibre bends that cause biased temperature measurements induce more-than-average signal loss and thus biased temperature measurements at the stress location (blue curves, recorded at 12 AM on 27 July 2023 at 80 m). Here, a single sharp bent was caused to a fallen branch.

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