Woody buffer effects on water temperature: The role of spatial configuration and daily temperature fluctuations

Jochem Kail¹ | Martin Palt¹ | Armin Lorenz¹,² | Daniel Hering¹,²

¹Department of Aquatic Ecology, University of Duisburg-Essen, Essen, Germany
²Centre of Water and Environmental Research, University of Duisburg-Essen, Essen, Germany

Correspondence
Jochem Kail, Department of Aquatic Ecology, University of Duisburg-Essen, Universitätsstrasse 5, 45141 Essen, Germany. Email: jochem.kail@uni-due.de

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Abstract
Water temperature is a key driver for riverine biota and strongly depends on shading by woody riparian vegetation in summer. While the general effects of shading on daily maximum water temperature $T_{\text{max}}$ are well understood, knowledge gaps on the role of the spatial configuration still exist. In this study, the effect of riparian buffer length, width, and canopy cover (percentage of buffer area covered by woody vegetation) on $T_{\text{max}}$ was investigated during summer baseflow using data measured in seven small lowland streams in western Germany (wetted width 0.8–3.7 m). The effect of buffer length on $T_{\text{max}}$ differed between downstream cooling and heating: $T_{\text{max}}$ approached cooler equilibrium conditions after a distance of 0.4 km (~45 min travel-time) downstream of a sharp increase in canopy cover. In contrast, $T_{\text{max}}$ continued to rise downstream of a sharp decrease in canopy cover along the whole 1.6 km stream length investigated. The effect of woody vegetation on $T_{\text{max}}$ depended on buffer width, with changes in canopy cover in a 10 m wide buffer being a better predictor for changes in $T_{\text{max}}$ compared to a 30 m buffer. The effect of woody vegetation on $T_{\text{max}}$ was linearly related to canopy cover but also depended on daily temperature range $T_{\text{range}}$, which itself was governed by cloudiness, upstream canopy cover, and season. The derived empirical relationship indicated that $T_{\text{max}}$ was reduced by $-4.6^\circ\text{C}$ and increased by $+2.7^\circ\text{C}$ downstream of a change from unshaded to fully shaded conditions and vice versa. This maximum effect was predicted for a 10 m wide buffer at sunny days in early summer, in streams with large diel fluctuations (large $T_{\text{range}}$). Therefore, even narrow woody riparian buffers may substantially reduce the increase in $T_{\text{max}}$ due to climate change, especially in small shallow headwater streams with low baseflow discharge and large daily temperature fluctuations.

KEYWORDS
buffer strips, riparian vegetation, riparian zone, river, stream temperature, temperate ecoregion, woody cover

1 | INTRODUCTION

In aquatic ecosystems, water temperature is a key factor for the presence and abundance of all organisms, including fish (Barton et al., 1985; Daufresne et al., 2004) and macroinvertebrates (Durance & Ormerod, 2007; Vannote & Sweeney, 1980). Higher water temperature results in physiological stress, especially for cold-water fish. Moreover, the metabolic rate of...
biota and thus oxygen demand depends on water temperature. In addition, oxygen content decreases with increasing water temperature, which is most critical for heterotrophs in temperate rivers during summer when temperature is highest and oxygen contents lowest.

In summer, water temperature mainly depends on shortwave solar radiation input and emitted longwave radiation output (Webb & Zhang, 2004). Shading by woody riparian vegetation influences both of these heat fluxes and hence, is considered one of the main factors influencing water temperature in summer (Caisse, 2006; Webb et al., 2008), especially reducing daily maximum water temperature $T_{\text{max}}$ (Bowler et al., 2012). In temperate ecoregions, most small streams would be fully shaded under natural conditions and stream restoration often includes the re-establishment of woody riparian buffers. The effect of woody riparian vegetation on $T_{\text{max}}$ is generally appreciated. Nevertheless, several open questions remain that limit the targeted implementation of riparian restoration measures, particularly concerning the role of the spatial configuration of woody buffers. Besides the use of physical models (e.g., Beaufort et al., 2016; Loicq et al., 2018), empirical studies may help to shed light on the role of length, width and canopy cover used here to describe the spatial configuration of woody buffers.

There is limited empirical knowledge on the length or travel time needed for water temperature to adapt to a change in canopy cover and related shade level, and to reach a new equilibrium temperature. The few available studies reported contrasting results: A longer adaptation length was reported for heating due to a decrease in canopy cover (4 hr travel time corresponding to about 1.2 km river length in Rutherford et al., 2004), compared to the shorter adaptation length for cooling due to an increase in canopy cover (150 m in Zwieniecki & Newton, 1999, 0.3 km corresponding to ~1 hr travel time for a 50% downstream cooling in Davis et al., 2016). The adaptation length needed to reach new equilibrium conditions is a crucial information for river management to exploit the full potential of cooling by woody riparian buffers.

The role of woody riparian buffer width has been widely studied, indicating that even narrow buffers with a width of about 10 m provide most of the shading of forested reaches. Therefore, woody vegetation at this spatial scale is considered more relevant compared to wider buffers, but this depends on site characteristics (Sweeney & Newbold, 2014). It is highly relevant for river management to identify the most effective buffer width because buffers wider than 10 m are difficult to establish in densely populated or agricultural regions.

The level of shading increases with canopy cover in the riparian buffer. Most empirical studies compared forested, and hence fully shaded to deforested, unshaded sites, thus ignoring the gradual increase in canopy cover and shade level from fully unshaded to fully shaded conditions (Arismendi & Groom, 2019; Bladon et al., 2018; Johnson, 2004; Moore et al., 2005; Quinn et al., 2009). Only few studies considered different shade levels to establish statistical relationships with water temperature (Broadmeadow et al., 2011; Rutherford et al., 2004; Turschwell et al., 2016). Such relationships should be developed at spatial scales most relevant for water temperature, and hence, information on the effect of woody buffer characteristics like ‘length’ and ‘width’ as described above are needed. The resulting empirical relationships could be used to predict the effect of moderate changes in canopy cover and shade levels more relevant in river restoration and management because fully forested buffers are difficult to establish. Furthermore, several studies used the complement of diffuse non-interceptance to quantify shade levels (Davies-Colley & Quinn, 1998; Rutherford et al., 2004), a variable commonly used in scientific studies at the reach scale but rarely available for river management at larger scales. Empirical relationships using a simple proxy for shading like the ratio of tree height to river width or canopy cover (percentage of the buffer area covered with woody vegetation) might be more easily applicable for river managers.

Besides the spatial configuration of woody riparian buffers, shading effects on $T_{\text{max}}$ may be affected by other factors, which rarely have been considered in empirical studies. From modelling studies, it is well known that heated water with an excess temperature $T_{\text{ex}}$ cools until equilibrium temperature $T_{\text{eq}}$ is reached following an exponential decay function (Jobson, 1973). As a consequence, the effect of shading increases with excess temperature, i.e. the deviation of the incoming excess water temperature from the equilibrium conditions at full shading $T_{\text{ex}} - T_{\text{eq}}$. In the context of shading by woody vegetation, excess temperature depends on solar radiation input upstream of a river segment, that is, on cloudiness and upstream canopy cover, and corresponds to $T_{\text{max}}$ measured at the upstream start of a segment. Equilibrium temperature can be assessed but this needs data-intensive heat budget models. We hypothesized that daily minimum temperature $T_{\text{min}}$ can be used as an easily quantifiable proxy for $T_{\text{eq}}$ because it can be considered the maximum cooling at full shading (zero solar radiation input). There are additional energy losses during night due to for example, sensible heat and bed conduction resulting in $T_{\text{min}}$, being lower than $T_{\text{eq}}$. Nevertheless, daily temperature range $T_{\text{range}} = T_{\text{max}} - T_{\text{min}}$ at the upstream start of a river section potentially is proportional and a proxy for $T_{\text{ex}} - T_{\text{eq}}$.

Against this background, the objective of our study was to derive an empirical relationship between canopy cover and summer daily maximum water temperature $T_{\text{max}}$. This relationship should be applicable in river management to assess how changes in shading affect $T_{\text{max}}$, that is, how changes in canopy cover $\Delta$Cover (e.g., caused by river management) lead to a change in daily maximum water temperature $\Delta T_{\text{max}}$. We first investigated the adaptation length needed to adapt to changes in canopy cover and reach equilibrium conditions, and woody buffers of different width (10 and 30 m) to identify the most relevant spatial scales (length and width). Moreover, we used percentage canopy cover as an easily available proxy for shading. In addition, we investigated how daily water temperature range $T_{\text{range}}$ influences the change of $T_{\text{max}}$. More specifically, the following hypotheses were tested for small lowland streams:

1. $T_{\text{max}}$ reaches an equilibrium within an adaptation length of a few hundred metres downstream of a sharp increase in canopy cover (cooling), and within about 1 km downstream of a sharp decrease in canopy cover (heating).
2. Changes in canopy cover in 10 m wide buffers have a significant effect on $\Delta T_{\text{max}}$, implying that restoration of even narrow buffers can benefit water temperature in river management.
3. The effect on $\Delta T_{\text{max}}$ increases with the change in canopy cover. This effect increases with the deviation of excess temperature from equilibrium conditions, with daily temperature range $T_{\text{range}}$ being an appropriate and easily quantifiable proxy.

2 | METHODS

2.1 | Study area

We investigated seven small sand-bed streams located in the lowlands of western Germany in the temperate forested ecoregion of the central plains (Illies, 1978) between 51 and 52 degrees North (Figure 1). At the two meteorological stations located closest to the study reaches (A and B in Figure 1), mean annual precipitation (2005–2019) was 715 and 696 mm, respectively. Precipitation in the study period in summer 2011 (May to August) was similar (310 mm, 221 mm) compared to the long-term summer mean from 2005 to 2019 (292 mm, 260 mm). Mean air temperature was lower in the summer of 2011 (16.7°C, 16.4°C) compared to the long-term summer mean (17.3°C, 16.9°C). The study reaches were 3.6–4.4 km in length with a low to moderate slope of 0.5–6.4‰ and located one to 12 km from the sources (Table 1). Catchments were 6.1–39.1 km² in size at the downstream end of the study reaches. Land use strongly differed, with more than 40% forest cover in catchments of reaches 1, 3, and 5, and more than 50% cropland cover in catchments of reaches 2, 6, and 7. Wetted width, depth and flow velocity during the sampling campaign typically ranged between 0.8–3.7 m, 5–32 cm and 0.01–0.43 m/s, with mean values of 2.0 m (SD 1.0), 14 cm (SD 9) and 0.16 m/s (SD 0.13).

2.2 | Meteorological data

For two meteorological stations run by the German Meteorological Service and located near the study reaches, daily data on cloudiness were downloaded for the measurement period 08/2010 to 10/2011 from the Climate Data Center at https://cdc.dwd.de/portal/. Data from station A (5064 Tönisvorst) was used for streams 1 and 2 and data from station B (6337 Lüdinghausen-Brochtrup) for streams 3, 4, 5, 6 and 7 (Figure 1). Cloudiness for each day was reported in eights ranging from 0 oktas (clear sky) to 8 oktas (complete overcast).

**FIGURE 1** Study reaches (numbered 1–7) and meteorological stations (A, B) located in the lowlands of western Germany (left), and land use in the catchments of the study reaches (right)
2.3 Water temperature data

Water temperature was measured with HOBO Pendant Dataloggers HOBO UA-002-64 (Onset Computer Corporation) every 20 minutes between 08/2010 and 10/2011 at 10 locations in each study reach. Temperature loggers were more closely spaced around the main change in canopy cover along the reach, with five loggers placed up and downstream at distances of about 50 m, 100 m, 500 m, 1 km and 2 km, respectively (Figure 2). All loggers were placed at locations where flow velocity was representative for the section to avoid larger water temperatures at stagnant locations. Two loggers had to be excluded due to missing or incorrect GPS coordinates (S1 of stream 1 and S3 of stream 2).

The raw water temperature data were pre-processed: Days with several missing data were excluded. Obvious measurement errors of very low (e.g., −20°C) or very high (e.g., +50°C) values, records with a temperature difference >5°C between consecutive measurements, and single missing data were replaced by the mean of the adjacent values. Periods with potentially very low discharge, when loggers potentially had fallen dry or were affected by direct solar radiation warming, were identified and excluded. Time-periods when daily water temperature range suddenly increased and approximated or exceeded daily air temperature range were identified and excluded. This was true for short time periods (16–27 days) for two loggers in stream 5 (O2, S5) and one logger in stream 6 (S5) as well as for long time-periods in summer for the two most upstream loggers O1 and O2 in streams 6 and 7. Hence, these four loggers were excluded from the analysis.

The study was restricted to periods of dry weather conditions with no indication for substantial cooling by precipitation and related surface runoff, which otherwise would have masked the effect of woody vegetation on water temperature. For each stream, periods of dry weather conditions in the foliation period (May to August 2011) were identified as time-spans at which daily mean water temperature over all loggers of the reach did steadily increase or stayed constant for at least 3 days. The periods of the individual reaches occurred at

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**TABLE 1** Characteristics of the study reaches (numbering corresponds to numbers in Figure 1), catchment size and land use were quantified for the downstream end, distance to source measured for the upstream end of the study reaches

| Number | Name         | Reach length (m) | Channel slope (‰) | Distance to source (km) | Catchment size (km²) | Forest (%) | Cropland (%) | Urban (%) |
|--------|--------------|------------------|-------------------|-------------------------|---------------------|------------|--------------|-----------|
| 1      | Schaagbach   | 4,369            | 6.4               | 1.5                     | 6.0                 | 63.6       | 13.9         | 12.5      |
| 2      | Kranenbach   | 2,709            | 1.7               | 4.0                     | 39.1                | 19.3       | 48.2         | 25.0      |
| 3      | Rotbach      | 3,426            | 3.6               | 7.9                     | 31.9                | 59.3       | 15.8         | 11.2      |
| 4      | Brabecker Mühlenbach | 3,072  | 2.7               | 0.7                     | 7.6                 | 14.8       | 40.7         | 22.9      |
| 5      | Felsbach     | 2,967            | 1.0               | 4.1                     | 12.0                | 39.6       | 35.7         | 6.0       |
| 6      | Dümmer       | 2,950            | 0.5               | 5.8                     | 13.3                | 17.4       | 66.6         | 6.6       |
| 7      | Mussenbach   | 2,646            | 1.1               | 11.8                    | 22.9                | 11.5       | 62.9         | 4.5       |

**FIGURE 2** Locations of the temperature loggers along the seven study reaches (shown schematically, numbering of study reaches corresponds to numbers in Figure 1), loggers located in more open sections coded with an ‘O’, loggers in more shaded sections with an ‘S’
similar dates, indicating that the analysis indeed identified time-periods of dry weather conditions in the region. From these periods, only days with a cloudiness of less than 7 oktas were considered, that is, excluding days with nearly complete or complete overcast, thus only including days when shading by woody vegetation potentially affects water temperature. For the selected study days of each reach, daily maximum water temperature \( T_{\text{max}} \) for each logger was calculated.

2.4 | Canopy cover

Riparian buffers along the study reaches with a width of 10 and 30 m (each side of the stream) were delineated. Woody riparian vegetation in the riparian buffers was quantified using remote sensing. Orthophotos covering the study reaches, taken during the vegetation period from May to August and as close as possible to the study period 05/2011–08/2011, were acquired from the German Federal Agency for Cartography and Geodesy. This resulted in a mix of RGB and CIR images, mostly from 2011 and 2012, with few images taken earlier (2006, 2008 and 2009) or later (2015 and 2016). The first step of an object-based image analysis OBIA – the segmentation of the orthophotos into objects – was done using the multiresolution segmentation algorithm in the eCognition Developer version 9.3 (Trimble, 2018). The resulting objects clearly distinguished between grassy/herbaceous/scrub encroachment and canopy forming shrubs/trees, given the specific small-scale shadow pattern in canopies. The second step of classifying objects as woody vegetation (canopy forming shrubs and trees) was done manually by visual inspection to minimize misclassification rates, supported by information on the Visible-band Difference Vegetation Index VDVI and Normalized Difference Vegetation Index NDVI of the objects as indicators for vegetation cover. Based on this, the percentage of the riparian buffer area covered with woody vegetation was calculated, referred to as canopy cover in the following. From visual inspection, spruce trees rarely occurred in the riparian area and deciduous trees were dominant. LiDAR data were not analysed but based on shadows of objects of known height, shrubs and trees were assessed being at least about 2 m in height but mostly >5 m.

2.5 | Statistical analysis

To address the first hypothesis on the adaptation length needed to reach equilibrium water temperature, adaptation sections were identified with a similar canopy cover along several loggers downstream of a sharp and considerable increase or decrease in canopy cover. The two adaptation sections for investigating cooling downstream of a sharp increase in canopy cover by +63 and +61 percentage points, respectively, comprised loggers O5 to S4 of stream 6 and loggers S1 to S3 of stream 7 (Figure 2). The three adaptation sections to investigate heating downstream of a sharp decrease in canopy cover by –63, –60, and –77 percentage points comprised loggers O1 to O5 of stream 3, loggers S5 to O5 of stream 5 and loggers S4 to O4 of stream 1 (Figure 2). For each adaptation section, the downstream change in \( T_{\text{max}} \) was calculated for each study day as the difference between \( T_{\text{max}} \) of the logger at the sharp change in canopy cover and each downstream logger. The loggers of the two cooling and three heating adaptation sections were pooled resulting in 6 loggers for cooling and 14 loggers for heating at different downstream distances with a total sample size of 162 cooling and 476 heating measurements.

Mixed effect models were used for the following three analyses, with streams and loggers as random effects to account for the nested experimental design, and date as an AR-1 auto-correlation structure to account for a potential temporal auto-correlation of water temperature measurements of consecutive days. First, the downstream distance of the loggers from the sharp change in canopy cover was used as the only fixed effect to test if the response variable \( T_{\text{max}} \) significantly changed in downstream direction. A generalized additive mixed model (GAMM) was used because water temperature was assumed to change non-linearly until a new equilibrium is reached, and the smooth term was used to check for a significant effect of downstream distance. Second, the additive model was compared to a linear mixed model (LMM) to test if the relationship is non-linear and \( T_{\text{max}} \) approaches a new equilibrium. Third, the slope of the fitted trend line was computed at 200 equally spaced points to identify parts of the non-linear trend, where the 90% confidence interval of its local slope did not include zero, and hence, the non-linear trend can be considered to increase or decrease significantly (Simpson, 2011).

In the following analyses, we were not interested in absolute values of \( T_{\text{max}} \) but rather how changes in canopy cover \( \Delta \text{Cover} \) (e.g., caused by river management) affect \( \Delta T_{\text{max}} \). Therefore, both canopy cover and \( T_{\text{max}} \) in the study sections were compared to conditions directly upstream to investigate how the change in canopy cover in the study sections compared to upstream leads to a change in \( T_{\text{max}} \) in the study section.

To test the second hypothesis on the importance of woody vegetation in narrow buffers, loggers were grouped into 30 study sections. Loggers were combined to study sections with a length as close as possible to the adaptation length of 0.4 km identified in the previous analysis. This ensured that water temperature at the end of the sections was fully adapted to the canopy cover, resulting in a median section length of 430 m and a 10th to 90th percentile range of 338–744 m. In addition, a 0.4 km section directly upstream was demarcated for each study section. The changes in canopy cover in the 10 and 30 m buffer compared to the upstream section \( \Delta \text{Cover}_{10} \) and \( \Delta \text{Cover}_{30} \) were calculated, with positive values corresponding to an increase, and negative values to a decrease in canopy cover in the study section compared to upstream. In addition, the difference in \( T_{\text{max}} \) between the upstream section and the study section was calculated by comparing the loggers at the downstream end of each section, with negative \( \Delta T_{\text{max}} \) values corresponding to cooling and positive values to heating in the study section. \( \Delta T_{\text{max}} \) of each study section was calculated for each study day, resulting in a sample size of 930 \( \Delta T_{\text{max}} \) values from the 30 study sections.
Two LMM were used, with streams and study sections as random effects, date as an AR-1 auto-correlation structure, and ΔCover10 and ΔCover30 as the only fixed effect, respectively. The coefficients of the fixed terms ΔCover10 and ΔCover30 were compared to identify the buffer width having a larger effect on ΔTmax. In addition, model performance as described by AIC and marginal $R^2$ values were compared to identify the buffer width better suited to develop the empirical relationship.

To derive an empirical relationship between canopy cover and $T_{\text{max}}$ and for testing the third hypothesis on the effect of daily temperature range, the 30 study sections delineated in the previous analysis were used again. The LMM with ΔCover30 as the only fixed term was compared to a respective GAMM to investigate if the relationship is linear or non-linear. The third hypothesis emerged because a preliminary analysis during data pre-processing indicated a much larger effect of canopy cover on $T_{\text{max}}$ in early summer. These seasonal differences were quantified by comparing the effect of ΔCover10 on daily ΔTmax in two LMMs based on sub-datasets from May–June to July–August. We hypothesized that these seasonal differences were due to differences in daily temperature range as a proxy for the deviation of excess temperature $T_{\text{ex}}$ from equilibrium conditions at full shading $T_{\text{eq}}$. We considered daily minimum temperature $T_{\text{min}}$ at night as the maximum diurnal potential for cooling with zero solar radiation input and hence, daily water temperature range $T_{\text{range}} = T_{\text{max}} - T_{\text{min}}$ as a proxy for $T_{\text{ex}} - T_{\text{eq}}$. Most probably, the excess temperature of the incoming water compared to equilibrium conditions in the (shaded) river segment mainly depends on solar radiation input upstream, that is, on cloudiness and upstream canopy cover. However, besides differences in the specific weather conditions in the study period with less clouds and higher solar radiation input in early compared to late summer, there also might have been real seasonal differences in $T_{\text{range}}$. To test this hypothesis, all three factors potentially influencing $T_{\text{range}}$ – cloudiness, upstream canopy cover and month – were included as fixed effects in an LMM with daily $T_{\text{range}}$ as response variable, and tested for significance.

To finally test if the effect of canopy cover on water temperature depends on daily temperature range, $T_{\text{range}}$ at the upstream end of the study sections was included as an additional fixed effect in an LMM besides ΔCover10. The interaction term ΔCover10×$T_{\text{range}}$ as well as the two main terms were tested for significance.

In all GAMM and LMM, the maximum likelihood estimator (ML) was used to correct the degrees of freedom for nested models with the same random effects but different fixed effects to find the optimal fixed structure (Zuur et al., 2009). Each fixed effect was dropped at a time and the resulting nested model always compared to the full model using the likelihood ratio test (ANOVA) to test for significant effects of the fixed terms (significance of interaction terms was tested prior to the main terms). The final model was then refitted using the restricted maximum likelihood estimator (REML) and validated based on visual inspection of the normalized residuals plots to identify violation of normality and homogeneity. For non-nested models, where the likelihood ratio test cannot be applied, the AIC and marginal $R^2$ values were compared. Models with a difference in AIC values of <2, 2–5, and >10 units were considered very similar, similar, and different, respectively. All statistical analyses were performed in R, using the generic lme function for LMM, the mgcv package for GAMM as well as the R-scripts derivFun and tsDiagGamm described in Simpson (2011) to identify and visualize a significant increase or decrease in the trend lines (downloaded from the github repository at https://github.com/gavinsimpson/random_code).

3 | RESULTS

Water temperature steadily increased without reaching equilibrium downstream of the sharp decrease in canopy cover (−63 to −77 percentage points) along the 1.6 km downstream distance investigated (Figure 3). Therefore, it was not possible to derive an adaptation length for downstream heating. The non-linear smooth term of the GAMM was significant ($p < .01$) but the additive model was not significantly different from a simple LMM ($p = .36$) and only had 1.78 degrees of freedom. In the final LMM, visual inspection of the diagnostic plots showed an increasing spread of the residuals with downstream distance, indicating violation of homogeneity. This was most probably due to the study design of comparing downstream loggers to the most upstream logger of the adaptation sections (i.e., normalizing $T_{\text{max}}$ values by setting the most upstream logger to zero). As a consequence, any differences in the study days relating to e.g. humidity or wind speed resulted in increasing differences in $T_{\text{max}}$ and larger variance in downstream direction. Given this identifiable structure, the power of covariate variance structure was subsequently included in the LMM, allowing variance to increase with downstream distance. The resulting LMM had a significantly better variance structure ($L = 248.19$, $df = 1$, $p < .001$). Downstream distance as the only fixed effect was significant ($p < .01$) and the coefficient of 0.002 indicated that $T_{\text{max}}$ increased by 0.2°C per 100 m.

In contrast, water temperature reached equilibrium conditions downstream of a sharp increase in canopy cover (+61 to +63 percentage points) and the adaptation length for cooling was about 0.4 km and hence, only a few hundred metres as hypothesized (Figure 4). In the GAMM with downstream distance as the only fixed effect, the non-linear smooth term was significant ($p < .01$) and the additive model was significantly different from a simple LMM according to the likelihood ratio test ($p < .01$), indicating that the relationship was non-linear. This was already implied by the 2.51 degrees of freedom of the additive model compared to 1 degree of freedom of the linear model. The slope of the fitted trend line of the smoothing curve was significantly different from zero between a downstream distance of 0–381 m. Consequently, the minimum length for the study sections used in the following analyses was set to 0.4 km.

Canopy cover in the 10 m buffer had a larger effect and was a better predictor for $T_{\text{max}}$ compared to the 30 m buffer. In each of the two LMMs, the fixed terms ΔCover10 and ΔCover30 were significant ($p < .01$). The coefficients of −0.019 and −0.023 indicated that a maximum change in canopy cover by ±100% in the 30 and 10 m buffer would cause a maximum change in $T_{\text{max}}$ by ±1.9 and ± 2.3°C,
respectively. Furthermore, the AIC value of the LMM with \( \Delta \text{Cover}_{10} \) as the only fixed effect was \(-7.0\) units lower compared to the \( \Delta \text{Cover}_{30} \) model, indicating that models were different and \( \Delta \text{Cover}_{10} \) was a better predictor. Moreover, marginal \( R^2 \) of the \( \Delta \text{Cover}_{10} \) model was 23.1\% and about twice the marginal \( R^2 \) of the model with \( \Delta \text{Cover}_{30} \) as the only fixed effect (11.4\%). Consequently, \( \Delta \text{Cover}_{10} \) was used as predictor in the empirical relationship developed in the following.

The simple empirical relationship between canopy cover and water temperature with \( \Delta \text{Cover}_{10} \) as the only predictor and \( \Delta T_{\text{max}} \) as response was linear (Figure 5). The smooth term of the GAMM with \( \Delta \text{Cover}_{10} \) as the only fixed effect was significant \((p < .01)\) but the additive model was not significantly different from a simple LMM \((p = .87)\) and only had 1.03 degrees of freedom. The effect of canopy cover on water temperature was much larger in early summer compared to late summer. For study days in May and June, the respective LMM with \( \Delta \text{Cover}_{10} \) as the only fixed effect had a marginal \( R^2 \) of 48.8\%, being about twice the marginal \( R^2 \) of the complete dataset (23.1\%) and more than four times the marginal \( R^2 \) of the sub-dataset from July and August (10.7\%). The coefficient of \(-0.036\) indicated that the maximum change in canopy cover by \( \pm 100\% \) in the early summer period (May–June) would result in a \( \Delta T_{\text{max}} \) of \( \pm 3.6°C \) compared to a \( \Delta T_{\text{max}} \) of \( \pm 1.7°C \) in late summer (July–August). Cloudiness was significantly lower in early summer compared to late summer (Mann–Whitney U test, \( p < .05 \)). However, medians of 3.3 and 4.3 oktas were not much different given that values ranged from 0 to 5.7, quantile ranges...
overlapped, and hence cloudiness only partly explained the seasonal differences mentioned above.

Indeed, daily water temperature range $T_{\text{range}}$ depended not only on cloudiness ($\text{Cloud}$) measured in oktas but also on canopy cover in the 10 m buffer 0.4 km upstream in percentage cover ($\text{Cover}_{10\up}$), and season ($\text{Month}$ from May to Aug). In an LMM with $T_{\text{range}}$ as response variable, all three fixed effects were significant ($p < .01$) and the final model had a marginal $R^2$ of 48.5%. Dropping cloudiness from the full model resulted in the largest increase of +496.7 AIC units, indicating that $T_{\text{range}}$ depended most strongly on cloudiness. But nested models without $\text{Cover}_{10\up}$ (+30.9 units) and $\text{Month}$ (+69.8 units) also had higher AIC values and models were significantly different from the full model ($p < .01$), indicating that these variables also increased model performance. Based on the intercept and coefficients of the final LMM, the following empirical equation was used to assess $T_{\text{range}}$ in the study streams:

$$T_{\text{range}} = 9.79 - 0.478 \text{Cloud} - 0.028 \text{Cover}_{10\up} - 0.394 \text{Month}$$  \hspace{1cm} (1)

with $T_{\text{range}}$ in °C, cloudiness $\text{Cloud}$ given in oktas, canopy cover upstream in a 10 m buffer $\text{Cover}_{10\up}$ in percent, and $\text{Month}$ from May to August coded 5–8.

Including $T_{\text{range}}$ as a proxy for the deviation of excess temperature from equilibrium conditions improved the empirical relationship on the effect of canopy cover on $\Delta T_{\text{max}}$. In an LMM including $T_{\text{range}}$ at the upstream end of the study sections as an additional fixed effect besides $\Delta \text{Cover}_{10}$, the respective interaction term $\Delta \text{Cover}_{10} T_{\text{range}}$ was significant ($p < .01$), and the final model had a higher marginal $R^2$ of 34.6% compared to the simple model with $\Delta \text{Cover}_{10}$ as the only fixed effect (23.1%). Based on the intercept and coefficients of the final LMM, the following empirical equation was used to assess $\Delta T_{\text{max}}$ in the study streams.

$$\Delta T_{\text{max}} = 0.2706 - 0.0028 \Delta \text{Cover}_{10} - 0.0768 T_{\text{range}} - 0.005 \Delta \text{Cover}_{10} T_{\text{range}}$$  \hspace{1cm} (2)

with the change in daily maximum water temperature $\Delta T_{\text{max}}$ and daily temperature range $T_{\text{range}}$ in °C, the change in canopy cover in a 10 m buffer compared to upstream $\Delta \text{Cover}_{10}$ in percent, and $\Delta \text{Cover}_{10} T_{\text{range}}$ being the interaction term.

According to the final LMM and Equations (1) and (2), the largest effect in the study sections with their specific length, water width, depth, and flow velocity occurred at days with a cloudiness of 0 oktas in May. Increasing canopy cover by 100% compared to upstream would result in an upstream $T_{\text{range}}$ of 7.9°C and a cooling $\Delta T_{\text{max}}$ of −4.6°C; decreasing canopy cover by 100% would result in an upstream $T_{\text{range}}$ of 5.1°C and a heating $\Delta T_{\text{max}}$ of +2.7°C.

4 | DISCUSSION

In this study, we were interested in how the effect of shading on water temperature depends on the spatial configuration of the woody riparian buffers as described by buffer length, width, and canopy cover. Identifying the most relevant spatial scale for length and width was a prerequisite to develop an empirical relationship between canopy cover and summer daily maximum water temperature $T_{\text{max}}$ for small lowland streams in temperate ecoregions.

4.1 | Woody buffer adaptation length

As hypothesized, $T_{\text{max}}$ decreased and reached an equilibrium after a few hundred metres downstream of a sharp and considerable increase
in canopy cover. The rate of cooling decreased in downstream direction very similar to the exponential decay function for excess temperature used in water temperature models (Jobson, 1973). However, there was a slight counterintuitive increase in water temperature within the first 50 m downstream of the sharp increase in canopy cover. Most probably, this reflects the conditions in the field. The loggers in the adaptation sections were approximately but not perfectly placed at the change in canopy cover. Moreover, the first logger 50 m downstream of the sharp change may still have received some higher solar radiation input compared to the more downstream loggers because there still was some transition (e.g. still direct solar radiation input in flow direction). The adaptation length of 0.4 km corresponded to a travel-time of about 45 min given the mean flow velocity of 0.16 m/s. This is in good agreement with the water temperature change predicted by the modelling approach of Davis et al. (2016). We used our empirical equation to predict the change in daily maximum water temperature $\Delta T_{\text{max}}$ for a mean summer day comparable to the temperature metric used in Davis et al. (2016) with a moderate cloudiness (3 oktas) in mid-summer (June), and for an increase in canopy cover of 60 percentage points as observed in the adaption sections. Using this $\Delta T_{\text{max}}$ of 2.3°C together with the median width (1.8 m), depth (0.12 m), and flow velocity of the study sections, the model of Davis et al. (2016) predicts a very similar exponential decrease, with about 50 and 90% of the effect reached at 100 and 350 m downstream, respectively. This indicates a wide applicability of the modelling approach and calibration setting used by Davis et al. (2016) in comparable mid-latitude temperate regions, as well as a low confounding effect of groundwater cooling in our study sections, since the model does not consider groundwater effects. Furthermore, Broadmeadow et al. (2011) only observed a marginal increase in the cooling effect of woody riparian vegetation with riparian buffer length from 0.1 to 5 km, also indicating that an equilibrium water temperature was already reached after a few hundred metres.

In contrast, $T_{\text{max}}$ linearly increased downstream of a sharp and considerable decrease in canopy cover, not showing any non-linear trend and not approaching equilibrium conditions, at least within the 1.6 km downstream distance investigated, corresponding to a travel time of 2.8 hr. Rutherford et al. (2004) reported contrasting results. They observed a decrease in the heating rate in stream sections with a travel time of 2.7 hr and an equilibrium at about 30°C was reached after about 4 hr in their modelling study in comparable small and slow flowing streams. Possibly, the missing downstream decrease in the heating rate in our study was due to the lower absolute $T_{\text{max}}$ values, with 90% being below 20°C and none exceeding 27°C. The heat efflux by evaporation increases with absolute water temperature as well as absolute air temperature and related vapour pressure deficit. Given the lower absolute water temperature in our study sections, evaporation loss might have been too small to compensate for the heat influx by direct solar radiation (Mohseni & Stefan, 1999; Rutherford et al., 1997). In any case, the increase of daily maximum water temperature is limited because in long unshaded sections with long travel times, water undergoes both, times of the day with positive and negative heat budgets, resulting in small net water temperature changes (Rutherford et al., 2004). The differences in the adaptation length for cooling and heating indicate that they are determined by different processes.

### 4.2 Woody buffer width and the effect of narrow buffers

As hypothesized, canopy cover in the narrow 10 m buffer was a better predictor for water temperature compared to wider buffer of 30 m. This is to be expected and consistent with the modelling results of Sridhar et al. (2004) predicting largest water temperature reductions for canopies within 10 m to the stream bank. Woody vegetation in the study sections often consisted of single lines of trees directly along the river banks, resulting in large canopy cover in 10 m buffers and large reductions in $T_{\text{max}}$ but only covering parts of the 30 m buffer. In study sections with a large percentage cover in the 30 m buffer, trees were not necessarily located directly along the river banks, not resulting in a similar large shading effect and reducing the predictive power of canopy cover at this spatial scale. Moreover, canopies of the single tree lines were overhanging the stream as described in Rutherford et al. (2018), shading the whole water surface of the small streams. These results and observations support the findings on the importance of streamside woody vegetation in narrow buffers summarized in Sweeney and Newbold (2014). However, this only holds true if woody vegetation consists of large trees because shading of course depends on vegetation height (Rutherford et al., 2018). Moreover, a dense line of trees planted at regular intervals fixes stream banks, limiting natural channel dynamics and the formation of in-channel habitats, and hence, should be avoided in stream restoration projects.

### 4.3 Empirical relationships to predict the shading effect based on the change in canopy cover and daily water temperature range

The simple empirical relationship with $\Delta \text{Cover}$ as the only predictor resulted in a change in daily maximum water temperature $\Delta T_{\text{max}}$ of up to ±2.3°C when canopy cover in the 10 m buffer changes from fully unshaded to shaded or vice versa. This is a somewhat smaller effect compared to the +3.0°C heating reported in Rutherford et al. (2004) for the 45 min travel time of our study sections, and well below the cooling effect of −3.8°C and −4.0°C to −4.6°C reported in Turschwell et al. (2016) and Broadmeadow et al. (2011), respectively. Differences are most probably due to the focus on sunny days in literature. Cloudless days were excluded in Rutherford et al. (2004), maximum temperature in summer investigated in Broadmeadow et al. (2011) most probably representing cloudless days, and direct solar radiation was not a significant predictor in the statistical models of Turschwell et al. (2016), indicating that differences between days were small and solar radiation high at all study days. When looking at comparable sunny days with a cloudiness of 0 oktas in early summer, our empirical
relationships predict a large daily water temperature range $T_{\text{range}}$, and hence, a stronger heating of $+2.7\,^\circ$C and cooling of $-4.6\,^\circ$C (for the study reaches with a median length of 430 m). This is very close to the values reported in the literature given above, and larger compared to the $\pm2.3\,^\circ$C predicted by the simple empirical relationship that does not include $T_{\text{range}}$, and hence cannot differentiate between days with different cloud cover (days with 0–6 oktas included in the dataset). In conclusion, both our results and values from literature addressing similar short reaches (~0.5–1.0 km) of small first to second order streams indicated that the heating and cooling effect of woody riparian vegetation at sunny summer days is in the range of $+3\,^\circ$C and $-4$ to $-5\,^\circ$C, respectively.

In the final empirical relationship, $\Delta T_{\text{max}}$ depended not only on the change in canopy cover $\Delta\text{Cover}$ but also on $T_{\text{range}}$, which in turn was governed by season besides cloudiness and upstream canopy cover. We considered $T_{\text{range}}$ as an easily quantifiable proxy for the deviation of excess temperature from equilibrium conditions. The higher the excess temperature of the incoming water compared to the equilibrium conditions in a river section, the higher the cooling effect. This is consistent with the modelling results of Davis et al. (2016) and empirical data reported in Coats and Jackson (2020), where the cooling in a downstream shaded reach increased with water temperature in the upstream unshaded reach. It is reasonable that $T_{\text{range}}$ at the upstream start of the study sections increased with direct solar radiation input upstream, i.e. decreased with cloudiness and canopy cover upstream, but the seasonality of $T_{\text{range}}$ is less intuitive. Seasonal differences and a higher $T_{\text{range}}$ in spring or early summer were also observed at a continental scale (Ferencz & Cardenas, 2017) and in other lowland streams (Łaszewski, 2018). However, our results indicate that a higher $T_{\text{range}}$ in early summer is not due to missing foliage as speculated by Łaszewski (2018) because trees were already leafed, resulting in a significant effect of canopy cover on $\Delta T_{\text{max}}$ in May and June. Instead, a higher $T_{\text{range}}$ in early summer might have been due to higher heat effluxes compared to late summer. Energy loss to the channel bed and bank due to heat conduction increases with the difference between water and soil temperature (Davis et al., 2016). This difference is probably larger in early summer and decreasing with higher soil temperature during summer. While solar radiation input is the same for equidistant dates from the summer solstice (20.06), soil temperature is lower start of May compared to end of August, possibly resulting in a larger $T_{\text{range}}$ in early compared to late summer. Indeed, visual inspection of the seasonal plot of monthly mean $T_{\text{min}}$ and $T_{\text{max}}$ showed such a decreasing difference in $T_{\text{range}}$. Since the increase in $T_{\text{min}}$ lagged behind the considerable increase in $T_{\text{max}}$ in early summer, $T_{\text{range}}$ was highest until June, but decreased afterwards due to a larger increase in $T_{\text{max}}$ compared to $T_{\text{min}}$ in late summer.

### 4.4 Transferability of results

Transferability of these results is most probably limited to summer low flow in small streams. Any decrease of the water surface receiving solar radiation input compared to the water volume decreases daily maximum water temperature (Rutherford et al., 1997). $T_{\text{range}}$, and hence, the potential for cooling by canopy cover. In rather rectangular cross-sections typical for managed streams, water depth increases linearly with discharge, while width is rather constant. Higher discharges dampen daily water temperature fluctuations and the potential for cooling by canopy cover, because a larger volume of water has to be heated. Therefore, variation in discharge and related wetted width and depth may explain much of the scatter in the empirical relationship and might be included as explanatory variable in future studies. Furthermore, diel fluctuations usually decrease with stream size (Ferencz & Cardenas, 2017; Vannotte & Sweeney, 1980) and this decrease in $T_{\text{range}}$ limits the potential for cooling by canopy cover in larger streams. The principles how daily water temperature fluctuations and rates of warming and cooling caused by canopy cover decrease with stream size are well established. However, so far studies have mainly focused on small streams where the largest effects can be expected and studies comparing different stream sizes or types are rare: The empirical data reported in Coats and Jackson (2020) clearly indicated that the effect of canopy cover on water temperature decreases with catchment size. The modelled effect of 60% canopy cover on daily maximum water temperature was about $-3.5\,^\circ$C in small headwater streams (Loicq et al., 2018, which is surprisingly similar to the $-3.1\,^\circ$C predicted by our empirical equations for 0 oktas in May) and decreased to $-1\,^\circ$C in the lower part of the catchment about 300 km from the source.

Similar to our investigation, most studies on the effect of canopy cover on water temperature deal with reach-scale effects on daily maximum water temperature, which can be considered the peak of daily fluctuations superimposed on the general annual cycle of mean water temperature (Caissie, 2006). However, there is very limited knowledge on the large-scale and downstream effect of shading on mean water temperature (Sweeney & Newbold, 2014). A recent modelling study indicated that the cooling effect of canopy cover on mean water temperature may propagate downstream and river reaches in the downstream part of a network may benefit from restoring woody riparian vegetation in headwater streams (Beaufort et al., 2016).

## 5 Conclusion

Based on the results and discussion, the following conclusions can be drawn for river management in mid-latitude small streams:

Woody riparian buffers should be at least several hundred metres in length (about 45–60 min travel time) and canopy openings should be avoided to exploit the full potential of cooling, which is in the range of $-4$ to $-5\,^\circ$C and highest at sunny days in early summer. In contrast, the heating and increase in daily maximum water temperature in unshaded reaches is in the range of $+3\,^\circ$C within the first few hundred metres to a kilometre downstream, water temperature continues to increase several kilometres (several hours travel time) downstream and equilibrium conditions may only be reached at high water temperature.
Developing woody vegetation (large trees) in a 10 m buffer directly adjacent to the river bank is most effective and already provides most of the effect of wider buffers. These results indicate that buffer width is less important compared to length, and woody buffers should be as long as possible to prevent the continuous heating in unshaded reaches, similar to the conclusions drawn by Stanford et al. (2020). However, wider buffers up to 30 m are known to increase other functions like nutrient retention (Gericke et al., 2020; Sweeney & Newbold, 2014).

The percentage of the riparian buffer area covered with woody vegetation mapped on orthophotos is a good and easily available proxy for shading by woody riparian vegetation and might be used for large-scale assessments. Most probably this only holds true for small streams where even small trees already shade the whole wetted cross-section. In larger streams and rivers, additional information on tree height from LiDAR data together with stream width may be used to assess the share of the cross-section shaded by woody vegetation.

The cooling effect does not only depend on canopy cover but also on the deviation of excess temperature of the incoming water from equilibrium conditions in the river section, with daily water temperature range $T_{range}$ being an appropriate and easily quantifiable proxy. Streams with a high potential for cooling might be identified based on $T_{range}$.

In summary, largest effects at the reach-scale are to be expected from restoring long woody riparian buffers, which do not necessarily have to be very wide, in streams with large diel fluctuations (large $T_{range}$), for example, small shallow headwater streams with low base-flow discharge.

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DATA AVAILABILITY STATEMENT
The data that support the findings of this study are available from the corresponding author upon reasonable request.

ORCID
Jochem Kail https://orcid.org/0000-0003-4133-0973

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