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REFRESH

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Contributors: **R.C.M. Verdonschot, A.M. Van Oosten-Siedlecka, A. Besse-Lototskaya, P.F.M. Verdonschot, R. Johnson, E.A. Kristensen, A. Lorenz, E. Martí, M. Angels Puig, C. Romero, I. Pardo, L. García, Y. Hershkovitz**

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PU	Public	x
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Abstract

Our study showed that shaded reaches have a significant effect on the water temperature of lowland streams, both by cooling the water when its flows from an upstream open area into the forest and by having a downstream cooling effect when the water flows from the forest into an open area. Despite a temperature effect was commonly detected the magnitude of the effect differed considerably among streams. We showed that this was partly the result of the LAI of the riparian forest canopy and of the current velocity. Based on the presence of stenothermal macroinvertebrates, we detected an effect on soft-substrate inhabiting species, with more warm-stenothermic and potamal species in the open reaches and more crenal species in the shaded reaches of the streams, indicating that the cooling by the forest or warming in the open areas had consequences for the biota of the streams. Based on these findings, it can be concluded that planting wooded riparian zones is a legitimate stream temperature mitigation measure from which macroinvertebrates preferring relatively low stream water temperatures could benefit. Nonetheless, beforehand predicting the absolute temperature decrease initiated by a newly planted riparian zone is difficult, given the large differences detected among streams.

Effects of shading on stream water temperature and stenothermic macroinvertebrates; *a synthesis of the findings along the trans-European latitudinal climate gradient*

Authors: R.C.M. Verdonschot, A.M. Van Oosten-Siedlecka, A. Besse-Lotoskaya, P.F.M. Verdonschot

Introduction

The water temperature of a stream strongly influences a wide variety of chemical and biological processes, ranging from ecosystem respiration to growth and development of stream organisms. In many European streams, water temperature is increasing due to the ongoing effects of changes in land use (especially deforestation of riparian zones), hydromorphological modifications (ranging from channel engineering to dam building and water extraction) and climate change, which increases the magnitude of temperature changes (Van den Hurk et al. 2006, Caissie 2006, Daufresne et al. 2004; Durance & Ormerod 2007). Stream water temperature is mainly dependent on solar radiation and less on convection or conduction (Geijskes 1942; Sinokrot & Stefan 1993; Johnson 2003); therefore, stream water temperature is strongly affected by riparian forest removal. Canopy presence along the stream reduces the solar radiation, wind speed, and air temperature, thus reducing summer stream water temperature, especially influencing the maximum water temperature and daily oscillations (Moore et al. 2005). Studies have shown that riparian vegetation removal results in increases in both summer water temperature and diurnal temperature fluctuations (Burton & Likens 1973; Johnson & Jones 2000; Wilkerson et al. 2005).

In a large part of Europe, riparian wooded zones are only present as fragments within an agricultural or urban landscape. Most streams primarily run through open landscapes, resulting in water temperatures that are too high compared to their natural state, and this change is amplified by climate change. For some running-water organisms (the cold stenotherms), this increased temperature reaches or exceeds their upper thermal boundaries. Many taxa are unable to survive when temperatures exceed 16–20 °C (Furitger 2004; Langford 1971; Murray & Giller 1991; Pattee 1968; Brittain 1976; Wehrly, Willey & Seelbach 2003). The ever-increasing effects of rising temperatures—especially in multi-stress situations that are common in altered streams, where rising stream water temperature coincides with eutrophication and organic pollution—include increased respiration, leading to oxygen deficits, and the subsequent loss of sensitive species (Kernan, Battarbee & Moss 2010; Verdonschot et al. 2013).

Planting trees along streams is an effective measure to mitigate the rise of stream water temperatures (Marsh, Bunn & Rutherford 2005). However, only scarce information is available, for example, on the optimal length of riparian wooded zones or the degree and type of canopy cover. Such factors should be quantified to guide ecologically effective temperature mitigation management practices. The effects of open or forested stretches on stream temperature generally differ among streams, as the rate of temperature change depends on a number of driving factors, like discharge (Caissie 2006), seepage (Allan & Castillo 2007), stream dimensions (Ward 1985), and amount of shade (Bescheta et al. 1987; Larson & Larson 1996; Rutherford et al. 2004). Studies on temperature changes in open-to-forested transition zones along streams throughout the world have reported temperature decreases of up to 4–5 °C along shaded stream stretches (Burton & Likens 1973; Storey & Cowley 1997; Rutherford et al. 2004) and increases of up to 2.5–7 °C along open stream stretches (McGurk 1989; Rutherford et al. 2004; Wilkerson et al. 2005). However, most studies have examined only a few stream reaches, mainly because of the extensive fieldwork involved (Bowler et al. 2012), which narrows the applicability of the study results on a broader spatial scale. Moreover, methods and measured temperature parameters often vary among studies, hindering the application of meta-analyses.

In the present study, we investigated stream water temperature changes along shaded-to-open and open-to-shaded transitions in 35 lowland streams along a trans-European latitudinal climate gradient with wooded riparian zones alternating with open areas. Our main objectives were to quantify the effects of wooded riparian zone stretches on water temperature and if these effects have consequences for stenothermic macroinvertebrates. We expected that stream water temperature of shaded reaches would be buffered compared to open reaches and therefore, the cool stream water from riparian wooded zones warms up along downstream open areas, while relatively warm water flowing from open areas into forest fragments is cooled. Furthermore, we expected that these differences in temperature result in a higher number of cold-stenothermic species in shaded reaches in comparison to open reaches. In the latter warm-stenothermic species are expected to be more common. The results of this study provide a quantitative basis for ecologically successful stream temperature mitigation.

Methods

Study design and site selection

Streams were studied positioned in stream valleys with fragmented patches of deciduous forest along a trans-European latitudinal climate gradient (Sweden, Denmark, Netherlands-Germany, and Spain) (Table 1). Both streams with open-to-shaded and shaded-to-open transitions (19 shaded-to-open, 16 open-to-shaded) were investigated, preferably with reaches of approximately 2 km riparian forest with an average canopy cover higher than 50% and 2 km open fields. Other selection criteria were a maximum bankfull width of 5 m, a minimal groundwater influx to avoid confounding effects on the water temperature and absence of tributaries, dams or impoundments.

Effect of shading on water temperature

Time series of stream water temperatures were obtained for 5-16 months in 2010-2011, with the summer period included at all sites (Table 1). Water temperature was recorded at 20-minute intervals in each stream along transects in the open and in the shaded part of the reach in 2010-2011, using series of data loggers (HOBO Pedant Temperature/Light Data Logger UA-002-64; Onset Computer Corporation, Bourne, USA) installed 3 cm above the bottom substrate in the middle of the stream, in areas with well-mixed water and with moderate flow. The number of measuring points along the transects differed among streams as a result of differences in forest fragment and open area size and because of logger loss, but ranged from 3 to 5 loggers per reach. The most commonly used logger positions were 50 m, 100 m, 250 m, 1000 m and 2000 m from the edge of the riparian forest.

Since water temperature is influenced by both the amount of light entering the water as well as the hydromorphological characteristics of the stream channel, canopy cover, channel width and depth, and current velocity were derived for each of the reaches. Canopy cover was expressed as the mean leaf area index (LAI) using a LAI-2000 plant canopy analyser (LI-COR, Lincoln, USA) with a 270° view cap in August-September (n = 10 measurements per reach, taken just above the water surface on cloudy days with stable sky conditions). Latitude of the stream was used as a geographic/climatic parameter.

The absolute change in daily mean water temperature opposed to that of the upstream reach average was calculated for each of the downstream measuring points for both the daily average and the daily maximum temperature of the 5% days with the highest daily average water temperature in the upstream reach. The warmest days were chosen because these the effect of canopy cover increases with increasing temperature and warm days are most critical for cold-stenothermic organisms (Van Oosten-Siedlecka et al., *in prep*.).

To estimate the rate of change in water temperature difference with distance to the upstream shaded or open reach both a quadratic (initial fast decrease is followed by slower decrease) and a linear model (constant decrease) were fitted to the data using the least squares method. For each stream the initial rate of change was calculated and for the streams displaying a quadratic relationship also the point of no change was determined. The relationship between the initial rate of change in water temperature (steepest slope in quadratic function 100 m interval) and environmental parameters known to influence water temperature was studied by reduced rank regression with forward selection of variables and significance level corrected for the number of predictors by a Holm’s correction using Canoco for Windows version 5.0 (Ter Braak & Šmilauer, 2012). The relationship with latitude (climate parameter), LAI (degree of shading of the stream channel), current velocity and width, depth and W/D-ratio (stream dimension) was investigated. Preliminary tests showed that the stream dimension parameters were inter-correlated. Therefore the strongest predictor (depth) was chosen to represent this factor. Finally, it was tested if groups of streams displaying a linear, quadratic or no temperature change differed in the values of environmental parameters using One-way Analysis of Variance (ANOVA) and Tukey post hoc comparisons.

Stenothermic macroinvertebrates

Macroinvertebrate samples were taken from each of the water temperature logger sites in September-November 2010. Macroinvertebrates were sampled by using either a Surber sampler with 500 µm or 1 mm mesh (25 x 25 cm; 0.0625 m^2), or kick sampler with the same sample surface and net mesh size. Choice of apparatus depended on the habitat conditions at the sites, e.g. water depth. At each site two habitat types were sampled; soft and hard substrates. One habitat type sample consisted of three 0.0625 m^2 subsamples taken from the most dominant soft and hard substrate types present within stretches of 25-50 m stream length. In streams in the Netherlands and Germany no natural hard substrates were present. To make comparison possible bricks were used as artificial hard substrates. At least six weeks before sampling, four bricks were introduced at each logger site in order to provide stream macroinvertebrates sufficient colonization time. In several streams bricks were lost due to sedimentation. Here only soft substrate samples were used for analysis. Samples were preserved with formalin (4% final concentration) or ethanol (70% final concentration) immediately after collection, sorted, and identified to the lowest taxonomical level practical.

The series of macroinvertebrate samples taken per stream were pooled for the open and the shaded reaches. For each species recorded temperature range preference and stream zonation preference were derived from the freshwaterecology.info database (Schmidt-Kloiber & Hering, 2012). Since of many macroinvertebrate species little is known about its temperature preferences, stream zonation acted as an additional source of information on the temperature preferences of macroinvertebrates. For example, preference for crenal habitats is well known and can act to a certain degree as a proxy for cold-stenothermy (Hering et al. 2009). It was tested if there was a significant difference in number of cold-stenothermic and warm-stenothermic species between shaded and open reaches among streams. Similarly, it was tested is there was a difference in the number of taxa with a preference for the eucrenal and hypocrenal zones and for the potamal zone, with taxa coded with 5 or more points regarded as specialists for these zones (Hering et al. 2009) between shaded and open reaches. Soft and hard substrates were analysed separately. Significance of the differences was tested using Wilcoxon signed rank tests. Since the absolute number of cold-stenothermic and crenal taxa could be influenced by site specific environmental conditions a correlation matrix was constructed with latitude and yearly maximum water temperature, as well as stream width, which is inherently related to river zonation preference. Significance of the correlations was tested using Spearman rank correlations. Statistical tests were conducted in IBM SPSS Statistics version 19.0 (IBM Corp, Armonk, NY, USA).

Results

Effect of shading on water temperature

Open-to-shaded

The diel average and maximum water temperature of 12 out of the 16 streams along the trans-European gradient running from open-to-shaded decreased along the shaded reaches (Table 2). The shape of the relationship between distance and the difference in water temperature in comparison to the open reach differed among streams; linear relationships were more commonly found than quadratic relationships. For the streams which displayed a decrease in temperature, initial rate of change of the mean daily temperature after the transition from open-to-shaded was on average -0.26 °C per 100 m of shaded reach (range -0.85 °C to -0.02 °C). For the diel maximum temperature the initial rate of change was higher; -0.39 °C per 100 m (range -0.85 °C to -0.03 °C).

For the streams with a quadratic relationship the mean daily temperature plateaued on average at a distance of 0.83 km downstream the open-to-shaded transition (range 0.41 to 1.19 km). At that point the temperature difference opposed to the water temperature of the open reach was on average -2.47 °C (-0.93 °C to -5.89 °C). For the daily maximum temperature this point was reached at an average downstream distance of 1.07 km (0.37-1.92 km) with an average temperature difference of -3.95 °C (-1.78 °C to -6.56 °C). The streams displaying a linear relationship cooled slower in comparison to the streams with a quadratic relationship. For the mean daily temperature, the maximum distance to the open-to-shaded transition was on average 1.34 km (range 0.50-2.00 km), where an average decrease of -1.11 °C was recorded (range -0.40 °C to -3.29 °C). For the daily maximum temperature this was 1.11 km (0.45 -2.00 km) with a decrease of -1.49 °C (-0.73 °C to -3.09 °C).

The magnitude of the initial rate of change in both daily average and maximum temperature was singly explained by the LAI (T_{av}: variance explained = 43.3%, pseudo-F = 10.7, p = 0.020; T_{max}: variance explained = 45%, pseudo-F = 11.5, p = 0.0192). Stream water temperature decreased more rapidly as a result of shading in streams with a relatively high LAI in comparison to the streams with a relatively low LAI (Fig. 1). There was no significant effect of depth, latitude or current velocity on the rate of change recorded. Groups of streams displaying a linear, quadratic or no temperature decrease were compared to test for differences in environmental parameters. For T_{av} LAI turned out to be the only significant parameter ($F_{2,15}$ = 5.350, p = 0.020), with the streams displaying no decrease having a lower LAI in comparison to the streams displaying a decrease (Fig. 2). For T_{max} current velocity was lower in the streams displaying a quadratic relationship in comparison to the streams with no or a linear decrease ($F_{2,15}$=7.264, p = 0.008). Furthermore LAI was lower in streams displaying no decrease ($F_{2,15}$ = 6.127, p = 0.013) in comparison to the streams displaying a linear or quadratic relationship.

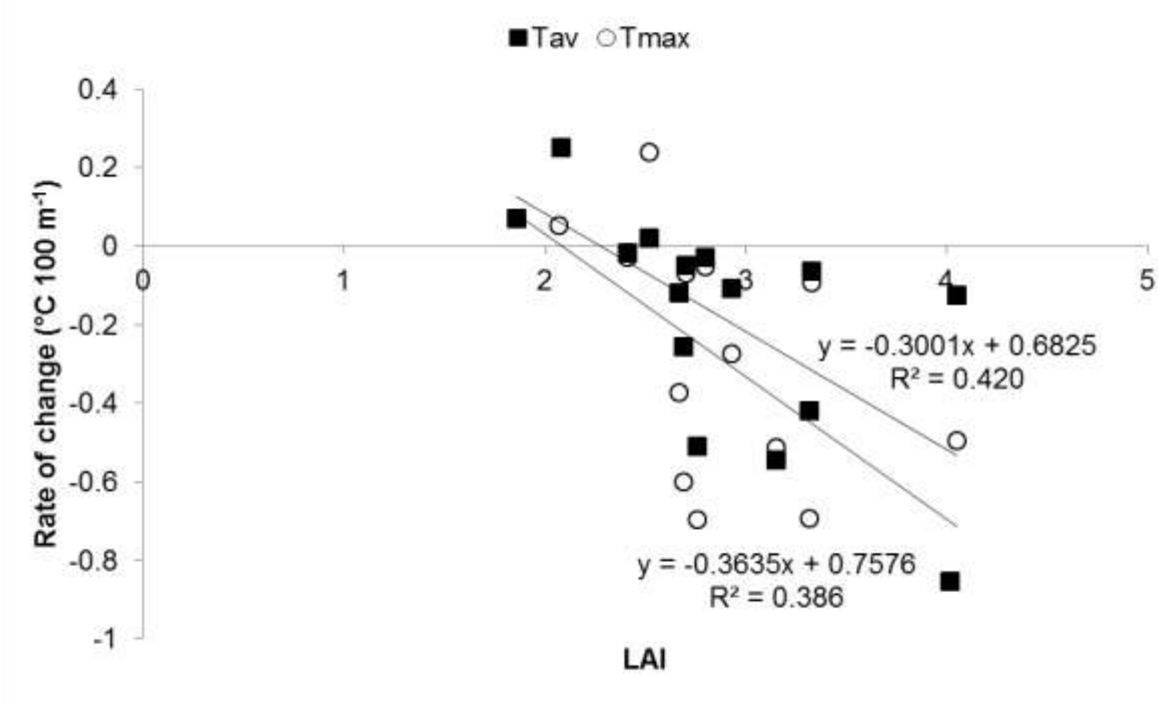

Figure 1: Relationship between rate of change in water temperature for the 5% warmest days of the year of European streams (n =16) when flowing from open to shaded and the LAI of the shaded reach.

Table 1: Characteristics of the streams studied.

Stream	**Country**	**Coordinates (latitude, longitude)**	**Gradient type**	**Open reach length (m)**	**Shaded reach length (m)**	**Record of observation**	**LAI Open**	**LAI Shaded**	**v (m/s)**	**Depth (m)**	**Width (m)**
Fibyan	Sweden	59 53.008, 17 21.133	Shaded-to-open	2000	1800	July 2010- June 2011	0.41 (0.33)	1.95 (0.31)	0.05 (0.05)	0.3 (0.1)	2.1 (0.6)
Jumkilsan	Sweden	59 59.700, 17 16.997	Shaded-to-open	2000	1000	July 2010- June 2011	0.42 (0.10)	1.42 (0.32)	0.08 (0.11)	0.4 (0.2)	3.0 (1.4)
Savaan	Sweden	59 55.970, 17 16.395	Shaded-to-open	1800	1200	July 2010- June 2011	1.63 (0.34)	3.03 (0.43)	0.06 (0.03)	0.4 (0.1)	2.7 (0.6)
Osterundaan	Sweden	59 49.444, 17 6.678	Shaded-to-open	2000	750	July 2010- June 2011	2.27 (0.21)	3.55 (0.19)	0.04 (0.04)	0.3 (0.1)	1.7 (0.6)
Lissan	Sweden	59 55.150, 17 47.397	Open-to-shaded	1500	1300	July 2010- June 2011	0.31 (0.13)	2.69 (0.68)	0.06 (0.05)	0.3 (0.1)	1.9 (0.4)
Runnabacken	Sweden	59 23.454, 16 6.105	Open-to-shaded	1000	2000	July 2010- June 2011	2.34 (0.76)	4.02 (0.27)	0.03 (0.03)	0.2 (0.1)	1.4 (0.6)
Skarendalsan	Sweden	58 51.121, 16 27.957	Open-to-shaded	2000	1200	July 2010- June 2011	0.74 (0.31)	2.80 (0.24)	0.16 (0.11)	0.4 (0.1)	3.2 (0.9)
Vitsan	Sweden	59 6.040, 18 5.660	Open-to-shaded	1900	1700	July 2010- June 2011	0.61 (0.15)	2.70 (0.57)	0.16 (0.12)	0.5 (0.2)	4.0 (1.4)
Storkesig	Danmark	56 11.343, 10 0.432	Open-to-shaded	265	500	June 2010- October 2010	0.39 (0.10)	3.32 (0.48)	0.30 (0.06)	0.2 (0.1)	2.1 (1.3)
Voel	Danmark	56 12.125, 9 41.495	Open-to-shaded	450	500	June 2010- October 2010	1.18 (0.29)	1.86 (0.42)	0.21 (0.08)	0.3 (0.1)	1.8 (0.5)
Linå Mollerup	Danmark	56 9.795, 9 43.446	Open-to-shaded	420	450	June 2010- October 2010	2.01 (0.19)	3.15 (0.18)	0.20 (0.08)	0.4 (0.1)	2.8 (0.9)
Gudenå	Danmark	55 51.611, 9 27.854	Open-to-shaded	500	500	June 2010- October 2010	0.83 (0.10)	2.08 (0.15)	0.26 (0.05)	0.6 (0.1)	3.8 (1.0)
Alsted Mølle	Danmark	55 50.872, 9 28.066	Shaded-to-open	600	600	June 2010- November 2010	0.98 (0.43)	2.28 (0.36)	0.45 (0.10)	0.4 (0.1)	4.0 (1.0)
Gesager	Danmark	55 51.171, 9 41.524	Shaded-to-open	1000	700	June 2010- October 2010	0.38 (0.07)	2.18 (0.16)	0.64 (0.15)	0.4 (0.1)	4.2 (1.6)
Skjold	Danmark	55 47.008, 9 59.223	Shaded-to-open	700	500	June 2010- October 2010	2.66 (0.29)	2.86 (0.43)	0.21 (0.09)	0.3 (0.1)	2.7 (1.1)
Urlev	Danmark	55 46.012, 9 46.794	Open-to-shaded	600	400	June 2010- October 2010	1.40 (0.33)	2.76 (0.36)	0.43 (0.33)	0.4 (0.1)	4.2 (1.9)
Ølsted	Danmark	55 51.451, 9 44.123	Shaded-to-open	500	450	July 2010- October 2010	0.74 (0.12)	2.45 (0.29)	0.41 (0.13)	0.4 (0.1)	3.8 (1.2)
De Aa	Netherlands	51 27.607, 5 04.627	Open-to-shaded	1350	2000	August 2010- September 2011	0.39 (0.07)	2.52 (0.05)	0.19 (0.10)	0.3 (0.1)	3.6 (0.6)

Stream *(continued)*	**Country**	**Coordinates (latitude, longitude)**	**Gradient type**	**Open reach length (m)**	**Shaded reach length (m)**	**Record of observation**	**LAI Open**	**LAI Shaded**	**v (m/s)**	**Depth (m)**	**Width (m)**
Groote Beerze	Netherlands	51 28.155, 5 14.547	Open-to-shaded	1400	1280	July 2010-August 2011	0.84 (0.20)	2.07 (0.24)	0.26 (0.12)	0.5 (0.3)	4.2 (1.3)
Ratumse beek	Netherlands	51 58.418, 6 49.094	Open-to-shaded	1200	2000	July 2010-November 2011	1.55 (0.28)	4.05 (0.34)	0.13 (0.11)	0.2 (0.1)	1.7 (0.5)
Zelsterbeek	Netherlands	51 15.913, 5 55.276	Open-to-shaded	1350	2000	July 2010-August 2011	0.69 (0.24)	2.41 (0.23)	0.17 (0.10)	0.5 (0.2)	4.5 (1.2)
Poppelsche Leij	Netherlands	51 29.201, 5 1.980	Shaded-to-open	2000	1560	July 2010-September 2011	0.81 (0.00)	3.37 (0.27)	0.26 (0.15)	0.3 (0.1)	3.0 (0.8)
Rovertsche Leij	Netherlands	51 29.035, 5 4.437	Shaded-to-open	2000	2000	July 2010-November 2011	0.08 (0.00)	2.04 (0.14)	0.13 (0.14)	0.4 (0.2)	4.2 (0.6)
Vlootbeek	Netherlands	51 07.439, 5 58.672	Shaded-to-open	1300	2000	July 2010-September 2011	1.02 (0.38)	2.99 (0.23)	0.18 (0.10)	0.2 (0.1)	3.1 (0.6)
Brabecker Mittelbach	Germany	51 35.610, 6 57.206	Shaded-to-open	2000	1500	July 2010-November 2011	0.41 (0.16)	1.50 (0.49)	0.18 (0.10)	0.1 (0.1)	1.4 (0.5)
Felsbach	Germany	51 58.119, 7 07.403	Shaded-to-open	1580	1200	July 2010-November 2011	1.63 (0.46)	3.16 (0.26)	0.18 (0.14)	0.1 (0.1)	2.0 (0.5)
Schaagbach	Germany	51 07.433, 6 11.088	Shaded-to-open	1250	3000	July 2010-November 2011	1.26 (0.34)	3.91 (0.29)	0.24 (0.13)	0.1 (0.1)	1.7 (0.5)
Rinnbach	Germany	51 49.436, 7 33.616	Open-to-shaded	1460	1400	October 2010-June 2011	0.53 (0.12)	2.67 (0.24)	0.09 (0.12)	0.2 (0.1)	2.2 (1.1)
Weierbach	Germany	51 39.881, 7 03.946	Open-to-shaded	1400	950	July 2010-October 2011	0.32 (0.10)	3.33 (0.20)	0.27 (0.15)	0.3 (0.1)	2.8 (0.7)
Riera d´Arbucies	Spain	41 45.614, 2 35.916	Shaded-to-open	1000	960	August 2010-January 2011	0.06 (0.03)	2.55 (0.58)	0.51 (0.14)	0.2 (0.2)	4.3 (-)
Riera de Pertegas	Spain	41 41.654, 2 29.175	Shaded-to-open	1000	1000	August 2010-December 2010	0.47 (0.28)	2.55 (0.30)	0.30 (0.13)	0.2 (0.2)	1.6 (-)
Riera de Santa Coloma	Spain	41 48.483, 2 42.852	Open-to-shaded	1000	800	September 2010-January 2011	-0.27 (0.29)	2.93 (0.61)	0.2 (0.09)	0.1 (0.1)	4.3 (-)
Riera de Canoves	Spain	41 38.593, 2 21.251	Shaded-to-open	1000	778	August 2010-December 2010	1.47 (0.45)	4.28 (0.29)	0.25 (0.11)	0.1 (0.1)	3.2 (-)

Table 2: Water temperature changes along shaded reaches of European streams in comparison to the mean upstream temperature (unshaded) for the 5% warmest days of the year. Only significant fits are shown ($p < 0.05$).

Stream	**Parameter**	**Function fitted**	**R^2**	**Initial rate of change(°C 100 m^{-1})**	**Downstream point of no change (quadratic)**		**Maximum difference measured (linear)**	
					Distance (km)	T difference (°C)	Distance (km)	T difference (°C)
Skarendalsan	T_{av}	Linear	0.34	-0.03			1.20	-0.50
	T_{max}	Linear	0.23	-0.05			1.20	-0.90
Vitsan	T_{av}	Linear	0.62	-0.05			1.70	-0.62
	T_{max}	Linear	0.49	-0.07			1.70	-1.02
Runnabacken	T_{av}	Quadratic	0.64	-0.85	1.15	-5.89		
	T_{max}	Quadratic	0.61	-0.85	1.17	-6.00		
Lissan	T_{av}	Quadratic	0.45	-0.26	1.19	-0.93		
	T_{max}	Quadratic	0.50	-0.60	1.04	-2.97		
Gudenå	T_{av}	Quadratic	0.15	+0.25	0.37	0.07		
Linå Mollerup	T_{av}	Quadratic	0.74	-0.54	0.58	-1.57		
	T_{max}	Linear	0.71	-0.51			0.45	-1.73
Storkesig	T_{av}	Linear	0.34	-0.42			0.50	-1.67
	T_{max}	Linear	0.44	-0.69			0.50	-3.09
Urlev	T_{av}	Quadratic	0.58	-0.51	0.41	-1.48		
	T_{max}	Quadratic	0.54	-0.69	0.37	-1.78		
Voel	T_{av}	Quadratic	0.13	+0.07	0.41	-0.08		
Weierbach	T_{av}	Linear	0.44	-0.07			0.90	-0.80
	T_{max}	Linear	0.19	-0.09			0.90	-1.00
Ratumsebeek	T_{av}	Linear	0.48	-0.12			2.00	-3.29
	T_{max}	Quadratic	0.38	-0.50	1.92	-6.57		
Rinnbach	T_{av}	Linear	0.64	-0.12			1.40	-0.84
	T_{max}	Quadratic	0.29	-0.37	0.85	-2.43		
Zelsterbeek	T_{av}	Linear	0.49	-0.02			2.00	-0.40
	T_{max}	Linear	0.36	-0.03			2.00	-0.73
De Aa	T_{av}	Quadratic	0.30	+0.02	0.59	0.08		
	T_{max}	Quadratic	0.26	+0.24	0.86	0.95		
Groote Beerze	T_{max}	Quadratic	0.18	+0.05	1.36	0.09		
Riera de Santa Coloma	T_{av}	Linear	0.54	-0.11			1.00	-0.75
	T_{max}	Linear	0.45	-0.27			1.00	-1.97

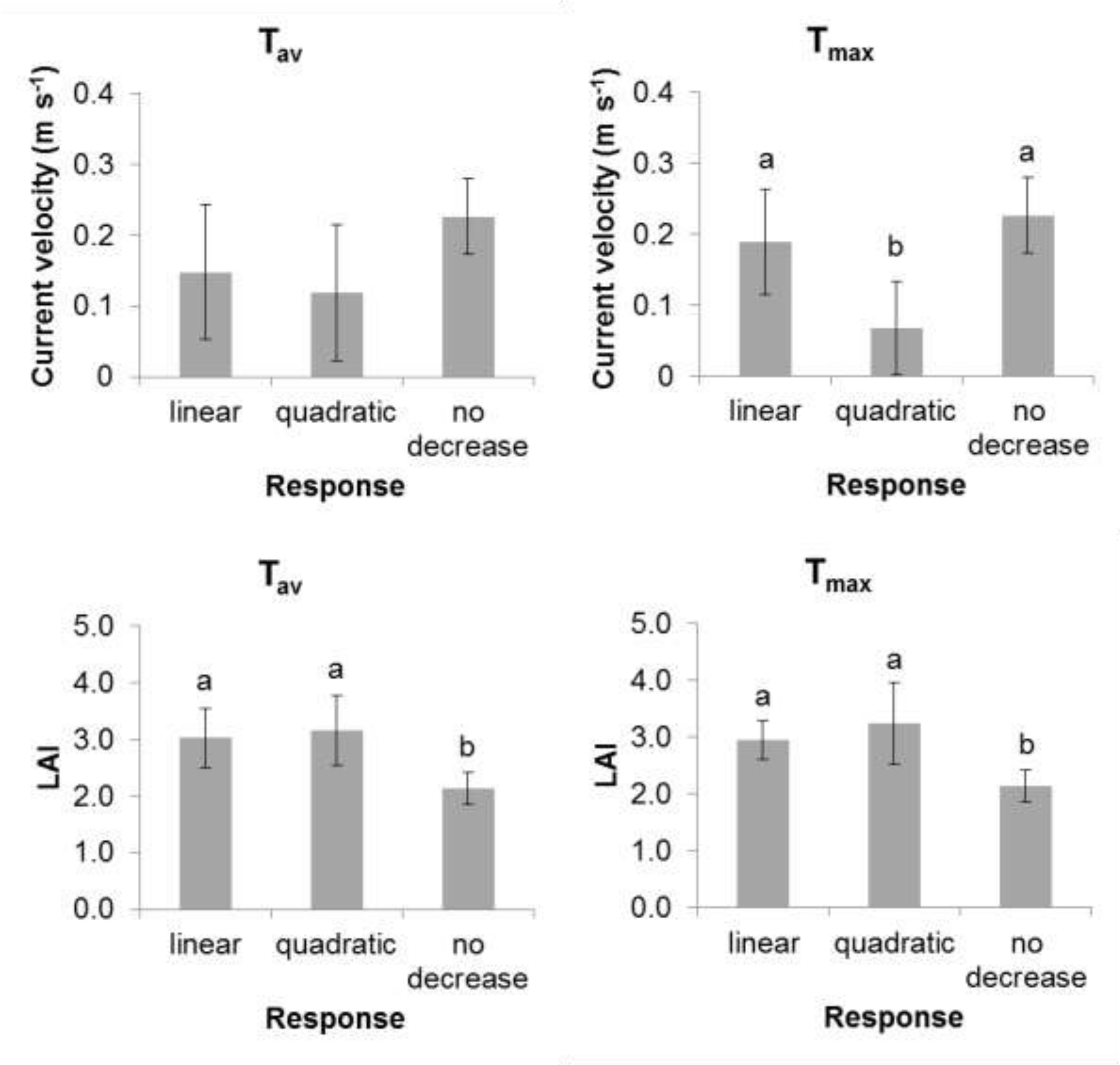

Figure 2: Comparison among groups of streams displaying a linear (n = 7), quadratic (n = 5) or no temperature decrease (n = 4) when flowing from open to shaded for mean shaded reach current velocity and LAI. Bars with different letters are significantly different (Tukey post-hoc comparisons, $p < 0.05$). Error bars indicate ±1 standard deviation.

Shaded-to-open

From the 17 streams included in the study 11 showed a significant temperature increase in the open reach (Table 3). Again both quadratic and linear relationships between the temperature difference and distance to the upstream shaded reach were found. Of the streams which warmed after leaving the forest, the initial rate of change in daily mean water temperature was on average 0.10 °C per 100 m, ranging from 0.04°C to 0.18°C between streams. For daily maximum temperature the initial change was 0.23 °C (0.06 °C to -0.59 °C per 100 m).

In the streams in which the warming plateaued downstream (quadratic fit), no further increase in mean daily temperature was predicted on average 1.47 km downstream in the open reach (range 0.79 to 2.55 km depending on the stream) and 1.30 km (0.76 to 1.97 km) for the maximum daily average, with a mean absolute increase of 1.14 °C (0.84 °C to 1.74°C) in mean daily temperature and 2.48 °C (1.78 °C to 4.08 °C) for the maximum temperature. For the linear functions at a distance of on average 1.29 km (0.4 to 2.0 km) a daily average temperature increase of 1.19 °C (0.14 °C to 1.94 °C) was observed. For T_{max} at a mean distance of 1.29 km (0.4 to 2.0 km) a mean temperature increase of 2.03 °C (0.27 °C to 5.45 °C) was recorded.

There was no significant relationship between the rate of change and any of the environmental parameters measured for the daily mean (eigenvalue = 0.3302, F-ratio = 5.9148, p = 0.2763) and daily maximum temperature (eigenvalue = 0.3477, F-ratio = 6.3974, p = 0.23820). Groups of streams displaying a linear, quadratic or no temperature increase were compared to test for differences in environmental parameters. For T_{av} current velocity turned out to be the only significant parameter ($F_{2,16}$= 7.075, p = 0.008), with the streams displaying no temperature increase having a higher current velocity in comparison to the streams displaying an increase in temperature (Fig. 3). For T_{max} current velocity was higher in the streams displaying no relationship in comparison to the streams with a linear or quadratic increase ($F_{2,16}$ = 23.948, p = 0.000).

Table 3: Water temperature changes along open reaches of European streams in comparison to the mean upstream temperature (shaded) for the 5% warmest days of the year. Only significant fits are shown (p <0.05).

Stream	**Parameter**	**Function fitted**	**R^2**	**Initial rate of change (°C 100 m^{-1})**	**Downstream point of no change (quadratic)**		**Maximum difference measured (linear)**	
					Distance (km)	T difference (°C)	Distance (km)	T difference (°C)
Riera de Canoves	T_{av}	Linear	0.98	0.15			1.00	1.94
	T_{max}	Linear	0.97	0.41			1.00	5.45
Osterundaan	T_{av}	Quadratic	0.54	0.18	0.79	1.19		
	T_{max}	Quadratic	0.32	0.26	0.94	1.78		
Savaan	T_{av}	Linear	0.71	0.04	-	-	1.80	0.58
	T_{max}	Linear	0.63	0.08	-	-	1.80	0.65
Jumkilsan	T_{av}	Quadratic	0.50	0.06	1.93	0.96		
	T_{max}	Linear	0.51	0.06	-	-	2.00	1.25
Fibyan	T_{av}	Quadratic	0.31	-0.13	1.29	-0.69		
	T_{max}	Quadratic	0.24	-0.24	1.27	-0.88		
Skjold	T_{av}	Linear	0.93	0.05	-	-	0.40	0.14
	T_{max}	Linear	0.38	0.11	-	-	0.40	0.27
Rovertsche Leij	T_{av}	Quadratic	0.44	0.10	2.55	1.27		
	T_{max}	Quadratic	0.43	0.20	1.77	1.91		
Schaagbach	T_{av}	Linear	0.46	0.08	-	-	1.25	1.34
	T_{max}	Linear	0.36	0.16	-	-	1.25	2.55
Brabecker Mittelbach	T_{av}	Quadratic	0.46	0.15	1.5	1.74		
	T_{max}	Quadratic	0.24	0.15	1.97	2.27		
Felsbach	T_{av}	Quadratic	0.35	0.09	1.2	0.84		
	T_{max}	Quadratic	0.23	0.19	1.18	1.89		
Poppelsche Leij	T_{av}	Linear	0.41	0.08	-	-	2.00	1.94
	T_{max}	Quadratic	0.10	0.33	1.16	4.08		
Vlootbeek	T_{av}	Quadratic	0.25	0.17	0.86	0.85		
	T_{max}	Quadratic	0.21	0.59	0.76	2.92		

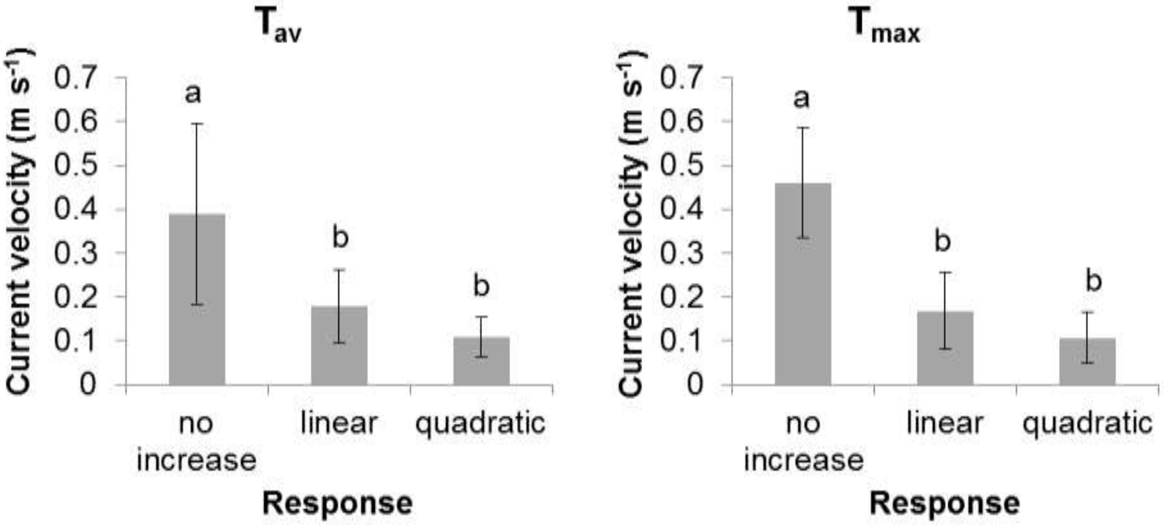

Figure 3: Comparison among groups of streams displaying a linear (n = 5), quadratic (n = 6) or no temperature increase (n = 6) when flowing from shaded to open for mean open reach current velocity. Bars with different letters are significantly different (Tukey post-hoc comparisons, $p < 0.05$). Error bars indicate ±1 standard deviation.

Stenothermic macroinvertebrates

Crenal species were more often encountered in the shaded reaches, whilst higher numbers of potamal species were found in the open reaches (Table 4). This difference was only present for the samples taken from soft sediments. There was no difference in number of species between hard substrates in the open and shaded stretches. In the open reaches more warm stenothermic species were found, but again only on the soft substrate. No differences were found for cold stenothermic species, but they were very rare in the streams studied.

Table 4: Comparison of the number of stenothermic macroinvertebrates on hard and soft substrates in open versus shaded reaches of European streams (n = 27 hard, n = 34 soft). Besides using the temperature range preference directly, stream zonation preference is given as a proxy for stenothermy with crenal linked to cold-stenothermy and potamal to warm-stenothermy.

Parameter	Categories	Substrate type	no. taxa stream open		no. taxa stream shaded		Difference open-shaded		Wilcoxon signed ranks test	
			av	se	av	se	av	se	Z	p
Stream zonation preference										
	Crenal	hard	0.81	0.29	1.15	0.31	-0.33	0.27	-1.19	0.236
		soft	0.76	0.19	1.18	0.23	-0.41	0.15	-2.50	**0.012**
	Potamal	hard	2.52	0.48	2.33	0.38	0.19	0.32	-0.54	0.592
		soft	3.59	0.58	2.65	0.50	0.94	0.28	-3.05	**0.002**
Temperature range preference										
	Cold stenothermic	hard	0.22	0.10	0.26	0.10	-0.04	0.10	-0.38	0.705
		soft	0.21	0.07	0.12	0.06	0.09	0.08	-1.13	0.257
	Warm stenothermic	hard	1.19	0.35	1.15	0.26	0.04	0.22	-0.23	0.819
		soft	1.65	0.29	1.26	0.21	0.38	0.17	-2.17	**0.030**

The number of crenal species in the shaded reaches on soft substrates correlated with reach width (ρ = -0.502, p = 0.002), indicating that in smaller reaches more crenal species could be found. As a result, stream zonation preference contains a component of stream dimension and could not be used as a full substitute for temperature range preference. There was a correlation between latitude of the stream (ρ = 0.409, p = 0.016) as well as the yearly maximum temperature in the shaded reaches (ρ = -0.421, p = 0.013) and the number of crenal species. This showed that more crenal species could be found on the higher latitudes, whilst the number of crenal species decreased with an increase in yearly maximum temperature. Not surprising given the different climatic zones covered in the study, there was a significant negative correlation between latitude of the stream and the yearly maximum temperature in the shaded reaches (ρ = -0.487, p = 0.004). Neither for the number of crenal species on hard substrates no significant correlations were detected, nor for the number of potamal species in the open reaches of the streams. For the temperature range preference of the species on soft and hard substrates only the number of soft-substrate inhabiting cold-stenothermic species in the shaded reaches correlated with latitude (ρ = -0.421, p = 0.024), indicating that on higher latitudes more cold-stenothermic species were recorded.

Conclusions

Our study showed that shaded reaches have a significant effect on the water temperature of lowland streams, both by cooling the water when its flows from an upstream open area into the forest and by having a downstream cooling effect when the water flows from the forest into an open area. Despite a temperature effect was commonly detected the magnitude of the effect differed considerably among streams. We showed that this was partly the result of the LAI of the riparian forest canopy and of the current velocity. Based on the presence of stenothermal macroinvertebrates, we detected an effect on soft-substrate inhabiting species, with more warm-stenothermic and potamal species in the open reaches and more crenal species in the shaded reaches of the streams, indicating that the cooling by the forest or warming in the open areas had consequences for the biota of the streams. Based on these findings, it can be concluded that planting wooded riparian zones is a legitimate stream temperature mitigation measure from which macroinvertebrates preferring relatively low stream water temperatures could benefit. Nonetheless, beforehand predicting the absolute temperature decrease initiated by a newly planted riparian zone is difficult, given the large differences detected among streams.

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