

THE INFLUENCE OF RIPARIAN SHADE ON LOWLAND STREAM WATER TEMPERATURES IN SOUTHERN ENGLAND AND THEIR VIABILITY FOR BROWN TROUT

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ABSTRACT

Suitable thermal conditions in streams are necessary for fish and predictions of future climate changes infer that water temperatures may regularly exceed tolerable ranges for key species. Riparian woodland is considered as a possible management tool for moderating future thermal conditions in streams for the benefit of fish communities. The spatial and temporal variation of stream water temperature was therefore investigated over 3 years in lowland rivers in the New Forest (southern England) to establish the suitability of the thermal regime for fish in relation to riparian shade in a warm water system. Riparian shade was found to have a marked influence on stream water temperature, particularly in terms of moderating diel temperature variation and limiting the number of days per year that maximum temperatures exceeded published thermal thresholds for brown trout. Expansion of riparian woodland offers potential to prevent water temperature exceeding incipient lethal limits for brown trout and other fish species. A relatively low level of shade (20–40%) was found to be effective in keeping summer temperatures below the incipient lethal limit for brown trout, but *ca.* 80% shade generally prevented water temperatures exceeding the range reported for optimum growth of brown trout. Higher levels of shade are likely to be necessary to protect temperature-sensitive species from climate warming. Copyright © 2010 John Wiley & Sons, Ltd.

KEY WORDS: brown trout; climate change; habitat management; riparian shade; water temperature

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INTRODUCTION

Temperature regulates nearly all bio-chemical processes and is therefore a key factor determining the suitability of aquatic environments for organisms, particularly in affecting the behaviour, distribution and growth of poikilothermic aquatic organisms (Coutant, 1976; Langford, 1990). The threat of global warming has consequently stimulated considerable interest in climate effects, via air temperature, on water temperature (Mackey and Berrie, 1991; Stefan and Sinokrot, 1993; Eaton and Scheller, 1996) and the consequences of an altered thermal regime for river biota (Weatherley *et al.*, 1991; Webb and Walsh, 2004; Hari *et al.*, 2006).

The spatial and temporal thermal regime of a river is sensitive not only to a range of natural factors (geology, hydrology, topography and climate; e.g. Elliott, 2000; Rutherford *et al.*, 2004) but also to anthropogenic impacts (riparian land use and abstraction; e.g. Bourque and Pomeroy, 2001). As one of many factors affecting the ecology of fish, temperature is both significant and

multifarious. Fish respond to all aspects of the temperature regime, including the maxima and minima, seasonal and diel fluctuations, rates of change and the duration of extreme thermal events. Moreover, temperature can affect the metabolism and growth of invertebrates (Briers *et al.*, 2004), the timing of emergence (Durance and Ormerod, 2007) and community structure (Daufresne *et al.*, 2004), although thermal effects on emergence are not always apparent (Langford and Daffern, 1975). Potentially, alterations of stream thermal regimes may, therefore, alter the food resource available to predators, notably fish. Other important factors such as water quality and discharge also interact significantly with water temperature (Durance and Ormerod, 2009).

With respect to fish, salmonids are undeniably of high importance in UK rivers (e.g. Salmon and Freshwater Fisheries Act, 1975; Butler *et al.*, 2009) and markedly affected by physico-chemical conditions in rivers (Hendry *et al.*, 2003). All salmonids have high metabolic rates and oxygen demand, but brown trout (*Salmo trutta* L.) are amongst the most temperature-sensitive of British native fish species, typically thriving in temperatures below 20°C with an upper thermal limit of 24–30°C (Elliott *et al.*, 1995). High

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water temperature can be lethal to brown trout; they are particularly at risk during periods of low flow with concurrent reduced oxygen levels and increased pollutant concentrations (Environment Agency, 2006). The threat of climate warming to native cold-water fish species across southern England has been recognized as a key priority for research and action by UK Government (DEFRA, 2005).

Behavioural adjustment to variation in water temperature has also been shown in many fish species. When subject to thermal stress, fish will move to cooler water (Schulz and Berg, 1992; Langford, 1990). In the US, chinook salmon (*Oncorhynchus tshawytscha*) have been shown to use cool-water refugia to maintain their core body temperature as much as 2.5°C below the mid-river temperature (Berman and Quinn, 1991); lake populations are known to move deeper to cooler water in the summer (Reynolds and Casterlin, 1979).

Average summer temperatures are predicted to rise by 4–5°C across southern England by the 2080s as a result of climate change (UKCIP02 HadCM3 scenario; Hulme *et al.*, 2002). Air temperature is often used to predict stream water temperature (Webb and Nobilis, 1997) and it is probable that a 4°C increase in air temperature would lead to increases in water temperatures of a similar magnitude. The predicted consequences of this change are habitat loss and local species extinction (Eaton and Scheller, 1996; Durance and Ormerod, 2007). There are few long-term records of water temperature from the southern, lowland UK and no data on the responses of lotic fish to either temporal or spatial thermal discontinuities. Elsewhere (e.g. the Upper Rhône), however, an increase of water temperature of 1.5°C over 20 years has been associated with shifts in the population of thermophilic fish and invertebrate species (Daufresne *et al.*, 2004).

Shade cast by riparian vegetation can substantially modify the thermal regime of a watercourse (Malcolm *et al.*, 2004; Caissie, 2006) and, therefore, influence the potential survival of sensitive fish such as salmonids during extreme conditions. As and when the regional climate alters (e.g. Hulme *et al.*, 2002), the influence of riparian shade is likely to become increasingly important in protecting trout and salmon populations from thermal stress. Information is lacking, however, on stream water temperatures across a range of habitats in southern lowland catchments. This study was devised, therefore, to determine the potential of shading by riparian trees to moderate stream thermal regimes and thereby contribute to the future management of suitable conditions for salmonids. Specifically, the study aimed to (1) characterize and quantify the spatial and temporal variation of stream water temperature in relation to riparian shade cover and (2) consider the potential of riparian shade as a management tool to modify stream thermal regimes for salmonids under predicted regional climatic conditions.

MATERIALS AND METHODS

Field sites

The two study catchments are located in the New Forest, southern England, and form part of its drainage system (Langford, 1996). The Ober Water, a tributary of the river Lymington, flows south into the Solent; Dockens Water is a tributary of the river Avon (Figure 1). Both rivers are low conductivity and circumneutral 3rd order streams (Table I). They have catchments of low relief with soft substrates dominated by clay, sand and gravel derived from similar geologies, arising within Barton clays and passing into Barton sands in the lower reaches (Environment Agency, 1998). The high ground is formed by drift geology, with river terrace deposits of sand and gravel, and alluvial accumulations of fine sediments and peat in the valleys (Environment Agency, 1998). Both catchments are dominated by surface drainage, which makes them more responsive to fluctuations in air temperature and solar insolation than groundwater-dominated systems. Land use comprises a mixture of broad-leaved woodland, coniferous plantations, heaths, lowland mires, forest lawns and improved pasture. The level of riparian shade ranges from complete woodland cover over both banks to highly grazed, open lawns.

The New Forest has been designated a special area of conservation (SAC) due to the scale and combination of internationally important and threatened lowland habitats. The streams of the open forest support internationally threatened invertebrates species such as the southern damselfly (*Coenagrion mercuriale* Charpentier 1840) and a fish fauna comprising over 20 species (Langford, 1996). There are important populations of species subject to specific conservation measures including bullhead (*Cottus gobio* Linnaeus 1758) and brook lamprey (*Lampetra planeri* Bloch 1784).

In the past, the study streams were straightened and dredged to improve the drainage for silviculture and for the construction of a railway. Consequently, many of the reaches have become incised and detached from their floodplains (NFLP, 2006). The recent LIFE3 project involved the restoration of floodplain and mire habitats across the New Forest, between 2002 and 2006 (NFLP, 2006), including extensive alterations to the channel geometry and floodplain management along the Ober Water, and alterations to the riparian vegetation in both study catchments. Dockens Water and Ober Water were selected for study on the basis that they provided a range of open and shaded stream sections. They were also known to support a diverse fish community including thermally sensitive salmonids (brown trout) and other species of high conservation status such as the brook lamprey and bullhead (Langford *et al.*, 2010).

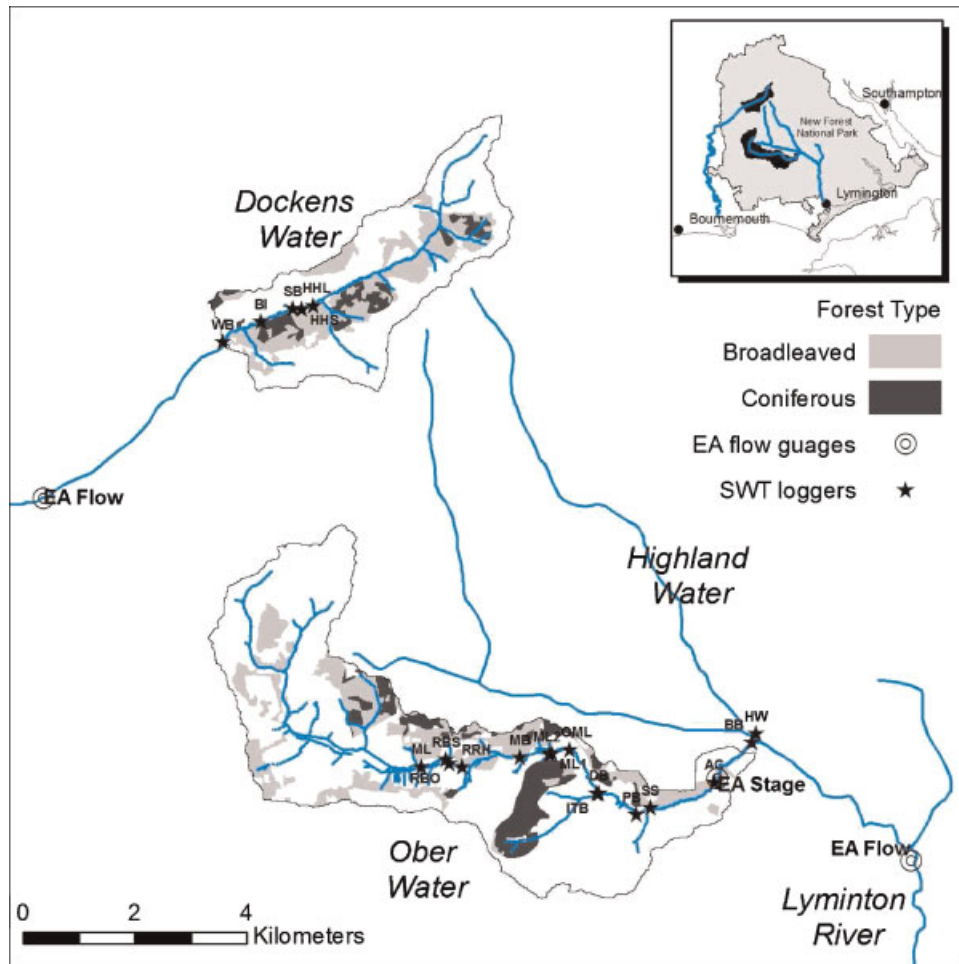


Figure 1. Map of study catchments in the New Forest, Southern England, showing location of temperature loggers and flow monitoring stations. SWT: stream water temperature loggers. Codes refer to named locations of loggers (see Table II). This figure is available in colour online at www.interscience.wiley.com/journal/rra

Data collection

Between January 2005 and January 2008, water temperature was monitored in the mainstream channel at four locations in the Dockens Water and five sites on the

Ober Water, plus one site in the adjacent Highland Water (Figure 1). Data were also available for 2006 for an additional site in the Dockens Water and eight further sites in the Ober Water. A summary of reach characteristics is provided in Table II.

Table I. Characteristics of the Ober Water and Dockens Water catchments

Attribute	Ober Water	Dockens Water
Catchment area	2298 ha	2166 ha
Distance from source to confluence with larger river	13.5 km	14.3 km
Typical pH ^a	7.1	7.2
Typical conductivity ($\mu\text{S cm}^{-1}$)	104	133
Altitude of source (AOD)	100 m	110 m
Area of forest within the catchment ^b (% of catchment)	644 ha (28)	581 ha (27)
Mean % riparian woodland cover within the catchment	27.6%	42.4%

^aEnvironment Agency (1998).

^bForestry Commission (2003).

Table II. Mean and maximum stream water temperatures at sites on the Ober Water and Dockens Water for 2005–2007. GSF is the global site factor (see methods for details); summer temperatures are for May, June and July; 500 m US is the % riparian cover (%) over the 500 m reach immediately upstream of each logger

Study reach	NGR	Distance from source (km)	Riparian shade cover		Summer T_{mean} (°C)			Summer T_{max} (°C)					
			Category	GSF	500 m US	2005	2006	2007	2005	2006	2007	T_{mean} (°C)	T_{max} (°C)
Ober water:													
Mill Lawn (ML)	SU230036	6.1	Open	0.989	0.3	16.4	17.4	15.6	19.3	20.5	18.0	11.6	27.7
Rooks Bridge (tributary A) (RBS)	SU235038	6.4	Shade	0.181	26.1	—	15.4	—	—	—	17.5	9.9	22.0
Rooks Bridge (tributary B) (RBO)	SU233036	6.4	Open	0.758	18.4	19.3	17.5	16.2	23.1	20.2	18.4	12.1	27.7
Red Rise Hill (RRH)	SU238036	6.9	Shade	0.164	42.4	15.8	16.8	15.8	17.8	19.2	17.5	11.1	25.2
Markway Lawn (channel A) (ML1)	SU254039	8.6	Open	0.972	19.9	—	17.7	15.1	—	22.7	18.1	10.4	34.5
Markway Lawn (channel B) (ML2)	SU257039	8.9	Open	0.980	7.3	17.6	18.1	16.4	21.9	22.7	19.7	12.0	31.1
Duck Hole Bog (DB)	SU263031	10.1	Partial shade	0.506	13.5	—	17.2	16.3	—	20.6	18.9	11.0	26.6
Puttles bridge (PB)	SU268028	10.6	Shade	0.202	44.4	15.6	16.6	16.2	17.5	18.4	18.1	12.0	24.5
Silver Stream (SS)	SU271028	11.2	Shade	0.379	64.0	—	16.2	15.7	—	18.5	17.5	10.6	24.1
Aldridge Campsite (AC)	SU283033	12.2	Shade	0.170	91.5	—	15.5	15.2	—	16.8	16.4	10.6	20.6
Bolderford Bridge (BB)	SU289041	13.2	Shade	0.232	81.5	15.1	15.8	15.3	16.3	17.1	16.6	11.0	22.0
Dockens Water:													
Holly Hatch Lawn (HHL)	SU211118	5.7	Open	0.711	18.3	15.6	16.2	15.3	17.8	18.5	17.0	10.8	26.3
Holly Hatch (HHS)	SU209118	5.9	Shade	0.197	46.4	14.8	15.1	14.5	16.3	16.7	16.1	10.0	21.6
Splash Bridge (SB)	SU207118	6.1	Partial shade	0.396	47.2	14.6	n.a.	14.6	16.6	n.a.	16.9	9.9	24.5
Broomy Inclosure (BI)	SU202116	6.9	Partial shade	0.372	33.8	14.0	14.9	14.6	15.0	16.4	15.9	9.9	21.3
Woodford Bottom (WB)	SU195112	8.0	Shade	0.128	62.2	—	13.5	14.0	—	14.3	14.9	9.9	19.8

Temperature was recorded using Gemini TinyTagPlus data loggers with an internal encapsulated thermistor. Loggers were secured to the stream bed using aluminium stakes driven in the soft substrate to a depth of at least 40 cm and positioned to drift just above the stream bed in all cases; each was set to log water temperature at 10 min intervals. Stated precision for the loggers is $\pm 0.2^\circ\text{C}$. In November 2006, all loggers were cross-calibrated over a range of 0–25°C in a laboratory water bath and found to differ by less than 0.7°C. Spot checks for accuracy were made when the loggers were downloaded: *in situ* temperature was determined using a hand held electronic thermometer (Hanna instruments HI 145-00) and measurements were related back to the contemporaneous logged values; there was no evidence of drift in accuracy over the period of the study.

Due to extremely low flow during 2006, the Dockens Water became a series of isolated pools maintained by interstitial flow. Some loggers became exposed to air for extended periods; data from these periods (i.e. air temperature) were removed from the record. Some gaps in the data record also occurred due to losses of loggers, delays in data uploading and equipment failure.

An automatic weather station (Delta-T) was installed in the Dockens Water catchment in March 2005. This station provides high temporal resolution meteorological data including rainfall, soil temperature (at 10 cm depth), air temperature and net solar radiation, logged at 30 min intervals.

For each reach in which stream temperature loggers were placed, broad physical characteristics were surveyed in the field or derived from digital OS maps (Table II). The riparian shade within a 100 m reach upstream from each logger was assessed using hemispherical photography. Images were taken between July and September using a 180° fish eye lens with the camera (mounted in a self-levelling gimbal) approximately 80 cm above the streambed. The images were analysed using Delta-T HemiView 2.1 canopy analysis software. The software calculates several canopy structure and gap light transmission indices. To measure the differences in effective riparian shade between the logger sites, the global site factor (GSF) was calculated. This parameter represents the proportion of global radiation (sum of direct and diffuse radiation entering through canopy gaps) under the plant canopy relative to that in the open and, therefore, provides a proportional estimate of potential energy flux. The hemispherical images were also used to calculate the mean % overhead canopy cover.

The riparian shade along the entire stream network in both catchments was assessed using geographic information system (GIS) software and aerial photographs taken in 2004. A digital stream network was created from the inland water theme of the OS MasterMap® topography layer, which includes all inland water features such as rivers, canals,

fishponds and pools. From this data set, the main stream, tributaries and major drains were selected to create the drainage network for each experimental catchment. A riparian buffer 30 m wide was created along the entire length of the network and used to clip the OS MasterMap[®] topography layer to generate a detailed map of riparian land use.

The level of canopy shade within individual riparian buffer polygons was classified as 0, 5, 10, 20, 30, 40, 50, 70, 80 or 100% based on the extent of riparian woodland canopy cover using digital aerial photographs. The area weighted mean riparian cover was determined within 100 m, 500 m, 1 km and 5 km long reaches upstream of each of the temperature loggers; stream tributaries were included in proportion to their relative contribution to the accumulated flow of the stream network. Where the two methods of assessing riparian cover overlapped (i.e. aerial photographs and hemispherical photography), they were found to agree well (r^2 0.756).

Summary temperature statistics were calculated for the studied reaches to elucidate the effects of riparian shade on daily maximum temperature (Caissie *et al.*, 2001; Wilkerson *et al.*, 2005), time in excess of key threshold temperatures (to reflect the thermal tolerance of key fish species; Elliott, 2000) and monthly mean temperatures (Stott and Marks, 2000).

RESULTS

Monthly mean temperatures

Variations in monthly mean stream temperatures were considered in terms of shaded vs. unshaded reaches and pools vs. riffles and glides (Figure 2). Monthly mean temperatures were shown to be highly consistent between sites in terms of temporal trends: the timing, direction and magnitude of month by month temperature changes were repeated across riffles and glides, and ponds in both open and

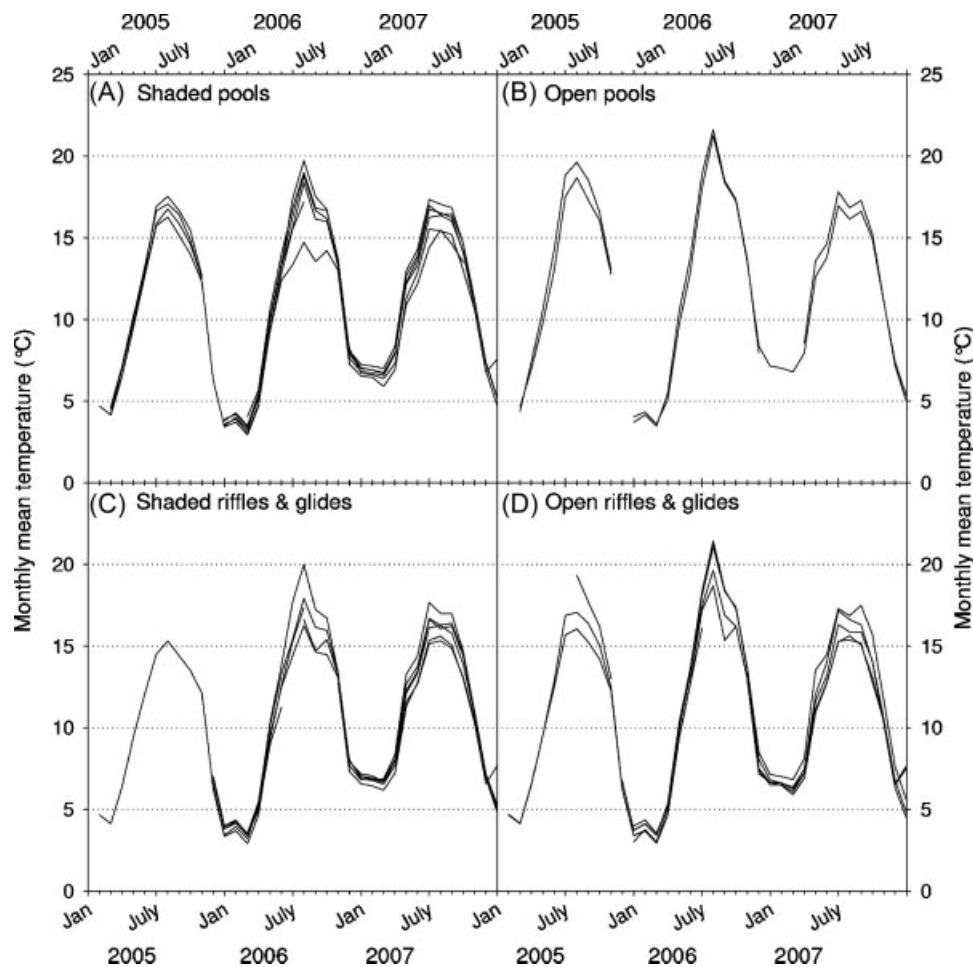


Figure 2. Monthly mean water temperatures recorded across all monitoring sites from January 2005 to December 2007. Multiple lines show data recorded at different sites on the Ober Water and Dockens Water

shaded reaches. Stream water temperature at all sites exhibited a sinusoidal annual pattern; in each year and at all sites the highest water temperatures were recorded in July. Where records were available for multiple sites of the same type, variation was most marked during summer months and relatively low during the winters. Peak summer mean temperatures tended to be higher by *ca.* 2°C in open pools than in shaded pools, although differences were greater in 2005 and 2006 than in 2007. Likewise, temperatures in open riffles and glides tended to be higher than in equivalent shaded reaches, but differences were again less apparent in 2007. There appeared to be little, if any, difference between the mean monthly temperatures for pools compared to riffles and glides for both shaded and open sites.

Three-year maximum and mean temperatures

Within the 3 years (2005–2007), the average water temperature (T_{mean}) across all sites ranged from 9.9 to 12.1°C and the maximum temperature (T_{max}) from 19.8 to 34.5°C (Table II). Shaded or partially shaded sites were characterized in general by lower T_{mean} (typically 10–11°C) than for open sites (typically 11–12°C), albeit with some inconsistencies. Puttles Bridge, for example, is a shaded site with relatively high T_{mean} , closely comparable to other, open sites on the Ober Water, whilst Markway Lawn (channel A) is an open site with a relatively low T_{mean} similar to other shaded sites. Differences in T_{max} were more consistent, with values for all shaded sites <26°C, compared to >26°C for all open sites.

Mean temperatures for May, June and July (hereafter referred to as ‘summer’ temperatures) in 2005–2007 ranged from 13.5 to 19.3°C and values for shaded sites were generally lower (13.5–16.8°C) than at open sites (15.1–19.3°C; Table II). Inter-annual variation was relatively low, varying by <3°C in all but one site (Rooks Bridge tributary A). Differences between years were generally higher for open (typically 1–3°C) compared to shaded sites (typically <1°C).

Maximum summer temperatures displayed a greater range of 14.3–23.1°C (Table II). Values for shaded sites were generally lower (14.3–19.2°C) than at open sites (17.0–23.1°C), as were inter-annual variations, which were typically 2.5–5°C for open compared to <2°C for shaded sites.

Diel variability

The mean monthly diel cycle of stream water temperature in the open and shaded sites is exemplified by the 2006 data for the Ober Water (Figure 3). In January 2006, the water temperature remained around 4.2°C at all the Ober Water sites throughout the day and the amplitude of the diel stream temperature range (<1.5°C) was lower than that of air

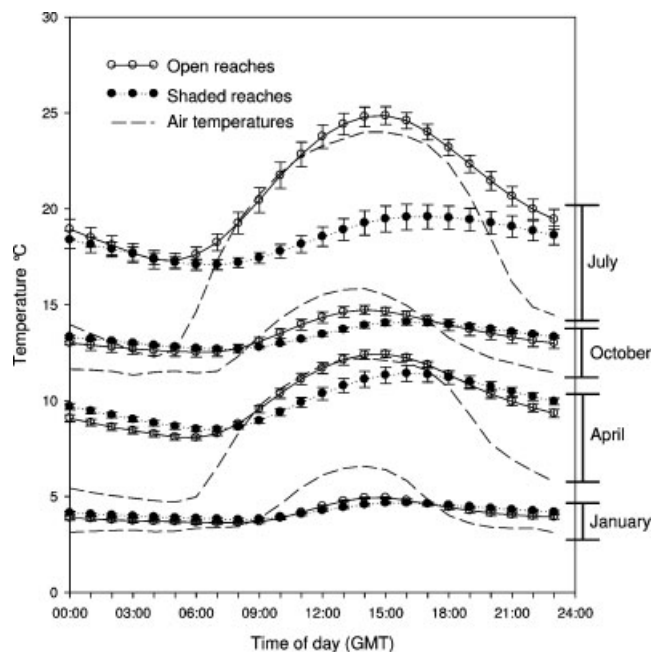


Figure 3. Mean diel variation of water (five sites) and air temperature (one site) in the Ober Water for January, April, July and October 2006. Vertical bars show standard error

temperature (3.5°C; Figure 4). The shaded sites were slightly cooler in the daytime and slightly warmer through the night, but differences were consistently <0.3°C (Figure 3). By April, the monthly mean temperature for both the open and shaded sites had increased to *ca.* 10°C and a clear difference had emerged in the diel range; 4.8°C for the open vs. 3.0°C for shaded sites (Figure 4). Shaded sites were up to 0.6°C warmer than those in the open at night but cooler by up to 1.4°C during daylight hours. By July, the

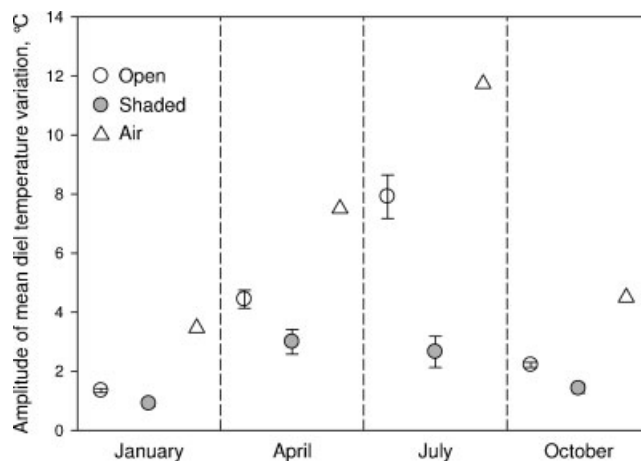


Figure 4. Amplitude of mean diel variation of water (five sites) and air temperature (one site) in the Ober Water for January, April, July and October 2006. Vertical bars show standard error for water temperature

mean monthly stream temperature and diel variation had risen to 20.9 and 7.9°C, respectively in the open, compared to 18.4 and 2.7°C in the shade. Daytime temperatures in open reaches were up to 5.5°C higher than those in the shade and, unlike in January and April, open sites remained warmer throughout the night (Figure 3). Water temperatures cooled through the autumn and, by October, the monthly mean had fallen to *ca.* 13.4°C at both open and shaded sites. The diel amplitude (Figure 4) remained higher (2.2°C) in the open than the shade (1.4°C), with shaded sites cooler during daytime (up to 0.9°C), but warmer through the night (up to 0.3°C; Figure 3).

Comparison of the diel variation in stream and air temperatures revealed that maxima in the stream at open sites were usually reached within 1–2 h of the maximum air temperature, compared to a longer lag of 2–4 h for shaded reaches (Figure 3). For example, water temperatures in April peaked at 14:30 GMT in the open vs. 16:00 in the shade, whilst in July, the open still peaked at 14:30 but the shaded sites did not peak until 17:00.

Thermal thresholds for brown trout

The number of days that stream water temperature exceeded thermal thresholds for brown trout showed high variation between sites (Figure 5). The upper limit for growth of 19.1°C as defined by Elliott *et al.* (1995) was exceeded at most sites in each year but generally for a longer period in the open compared to the shade. The same applied to the number of days the incipient lethal limit for brown trout of 24.7°C (Elliott *et al.*, 1995) was exceeded. In the worst case, during 2006, stream temperatures exceeded the growth limit on more than 90 days at four open sites and

the lethal limit on more than 40 days at two of these. In contrast, stream temperatures only exceeded the lethal limit for brown trout at one site and for 2 days during 2006. Statistical comparisons (Mann–Witney Rank Sum test) of the number of days over 2005–2007 that stream temperature exceeded both limits demonstrated statistically significant ($P < 0.001$) difference between shaded and open reaches.

Influence of upstream vegetation

To elucidate the influence of riparian woodland within the broader catchment, stream temperature variables (T_{mean} , T_{max} and the number of days water temperature exceeded the thermal thresholds for brown trout) were considered in relation to riparian cover for 100 m, 500 m and 1 km reaches upstream of the logger locations (Figure 6).

Variations in the overall T_{mean} for 2005–2007 (Table II) were largely independent of the extent of riparian woodland cover (Figure 6A) and did not differ with the length of upstream reach considered. Linear regression analysis (least squares) showed that the relationships between T_{mean} and % riparian cover for 100 m, 500 m and 1 km upstream (Figure 6A) were not statistically significant.

In contrast, there was a statistically significant linear relationship between summer T_{mean} and the level of riparian cover over 100 m ($p = 0.006$), 500 m ($p = 0.002$) and 1 km ($p = 0.002$) upstream (Figure 6B). The linear regressions derived for the three summers indicated that a 50% increase in riparian cover over 100 m, 500 m or 1 km would likely be associated with a reduction in T_{mean} of *ca.* 1°C. Likewise, summer T_{max} values were significantly linearly related to upstream % riparian cover ($p < 0.001$ for 100 m, 500 m and 1 km upstream riparian shade). The best fit linear regressions indicated that a 50% increase in upstream riparian cover would be associated with a decrease in summer T_{max} of *ca.* 2.0–2.3°C (Figure 6C). As for summer T_{mean} (Figure 6B) the relationship between summer T_{max} and upstream riparian cover differed little when cover was considered over 100 m, 500 or 1 km upstream reaches (Figure 6C).

In terms of the number of days per year that stream temperatures exceeded critical thresholds for brown trout (Figure 5), exceedance of the upper threshold for optimum growth (19.1°C) varied nonlinearly with upstream % riparian cover (Figure 6D). This relationship was significantly represented statistically ($p < 0.0001$ for 100 m, 500 m and 1 km upstream riparian shade) by a decay function (two parameter hyperbolic decay) for upstream riparian cover over 100 m, 500 m and 1 km and differed little when considered over different distances upstream (Figure 6D). The number of days per year that T_{max} exceeded the incipient lethal limit for brown trout (Figure 6E) also varied nonlinearly with % riparian cover upstream. T_{max} did not, however, progressively change with % cover but only

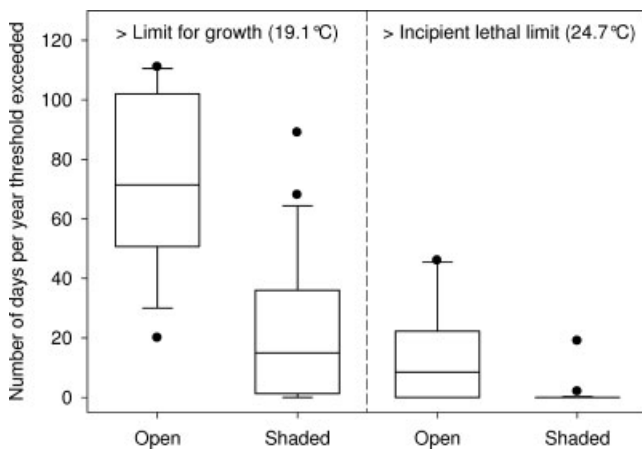


Figure 5. Number of days per year maximum daily temperature exceeded thermal thresholds for brown trout (Elliott and Elliott, 1995) at open and shaded sites on the Ober Water and Dockens Water, 2005–2007 (Median: bar; 25th and 75th percentiles: box; 10th and 90th percentiles: whiskers; outliers: ●)

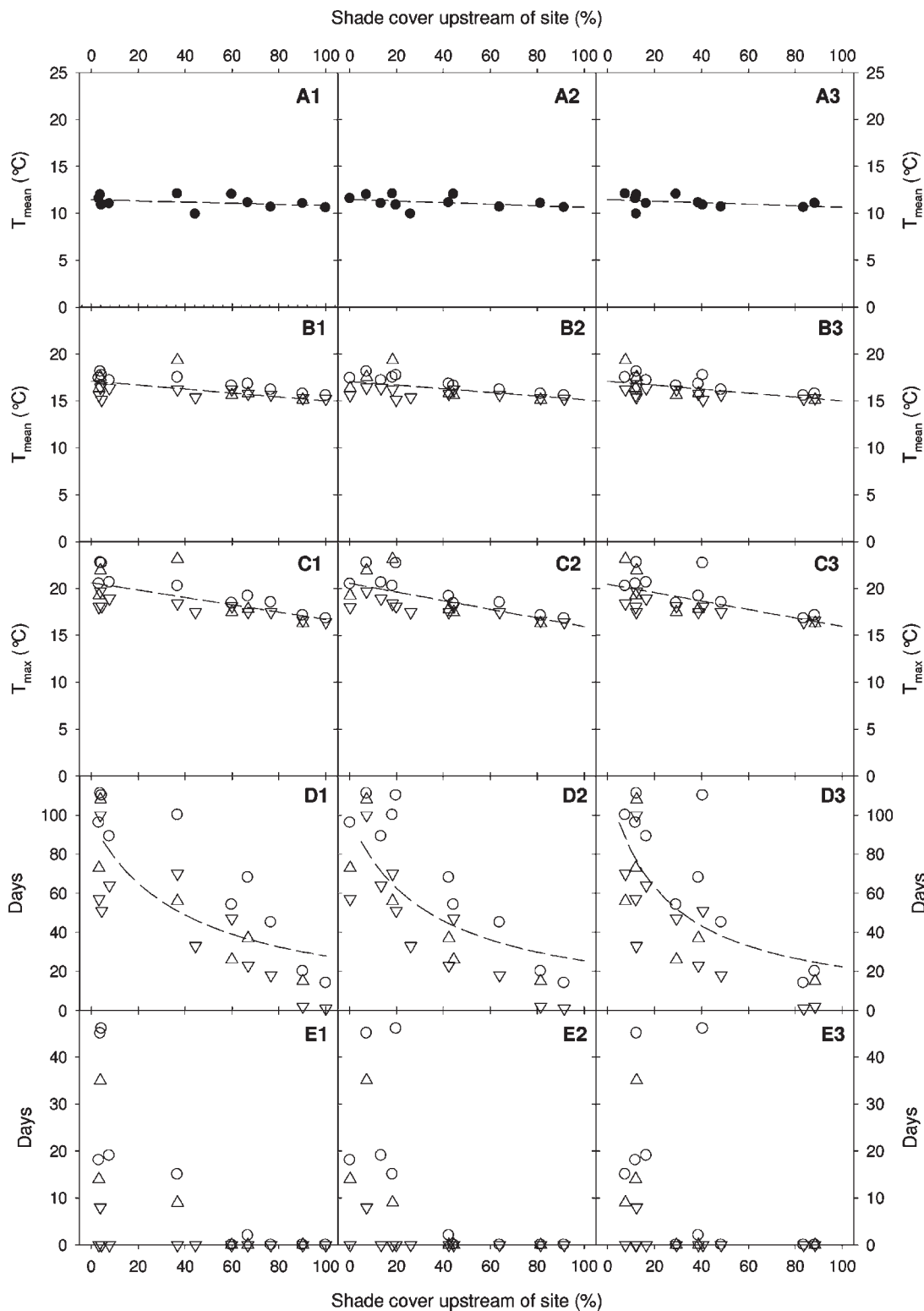


Figure 6. Stream water temperature parameters in relation to percentage riparian upstream cover for the Ober Water, 2005–2007. (A) Mean temperature 2005–2007, (B) Mean daily temperature during May, June and July, (C) Maximum daily temperature during May, June and July, (D) Days per year daily maximum temperature exceeded thermal limit for growth of brown trout, (E) Days per year daily maximum temperature exceeded the incipient lethal thermal limit for brown trout. (A1–E1) Riparian cover for 100 m upstream, (A2–E2) Riparian cover for 500 m upstream, (A3–E3) Riparian cover for 1000 m upstream. ▲2005, ●2006, ▼2007 for panels B, C, D and E

exceeded the lethal limit for more than two days per year at sites with less than *ca.* 20% riparian cover for 500 m upstream (Figure 6E2) and less than *ca.* 40% riparian cover for 100 m (Figure 6E1) and 1 km (Figure 6E3) upstream.

DISCUSSION

The present study investigated spatial and temporal changes in stream water temperature in two catchments of the New Forest as water flowed through mires, heavily grazed pasture and semi-natural woodland. Previous authors have characterized the thermal regime of lowland rivers but usually involving single locations towards the lower end of major river systems (Smith, 1968; Boon and Shiers, 1976; Webb and Walling, 1993; Webb *et al.*, 2003). In the UK, much research has investigated thermal conditions in upland streams subject to commercial afforestation with conifer plantations (Weatherley and Ormerod, 1990; Stott and Marks, 2000; Webb and Crisp, 2006).

The surface water dominated streams of the New Forest are very responsive to changes in air temperature and solar insolation and displayed marked diel (Figure 4) and seasonal variation (Figure 3) in water temperature, in sharp contrast to streams dominated by ground water (Webb and Zhang, 1999). At both the open and shaded sites, the annual cycle of solar radiation was clearly evident in monthly water temperature records (Figure 2). In 2005 and 2006 (years of broadly similar hydrological and climatological conditions), there was a consistent pattern in the inter-site variability (Table II) as reported for elsewhere (Webb and Crisp, 2006). In the present study, inter-site variability in mean and maximum temperatures reflected the level of riparian shade at the specific reach scale.

Our observations illustrate how water temperature is moderated by passage through open and shaded reaches. The extent of variation, however, differs according to specific temperature parameter. The % riparian cover upstream of a logger location, for example, is associated with relatively little variation in T_{mean} over 3 years (Figure 6A), but exerted a marked effect on summer T_{max} (Figure 6C). Net radiation has been shown to be the dominant heat source for streams through the summer (Hannah *et al.*, 2008); we suggest that riparian shade moderates maximum water temperatures in these catchments via reduction of direct insolation and the consequent suppression of the amplitude of diel temperature (Figure 4). Mean temperatures in open and shaded reaches are little different but the response of open sites to the marked diel fluctuation of air temperature (driven by insolation) leads to significantly higher temperature maxima in summer months.

Riparian shade, thus, affects both the timing and the magnitude of stream water temperature changes and substantially moderates the thermal regime of woodland

areas compared with sites with more open vegetation (Stefan and Sinokrot, 1993). This observation was most apparent for sites where the development of the riparian broadleaf tree canopy in the spring strongly influences shading of the stream below (e.g. Figure 2). Although inter-site variability through the winter is small, the pattern is consistent with open sites cooler during the day and warmer at night.

From a fishery perspective, New Forest streams are notable, having a rich fish fauna with over 20 species recorded including priority species for conservation (bullhead and brook lamprey). The most common species are minnow, bullhead, stone loach, lamprey and brown trout, with the fish biomass usually dominated by large individuals of chub, brown trout and eel (Le Cren, 1969; Mann, 1971; Langford, 1996; Gent, 2006). Observations in this study demonstrated that riparian shade is important in terms of regulating stream water temperature and the viability of New Forest streams for salmonid fish. The number of days that thermal thresholds for brown trout are exceeded (Figure 5), for example, amply demonstrated the value of riparian canopy shading at specific sites. Notwithstanding the predicted future alterations to local climate (e.g. Hulme *et al.*, 2002), evidence indicates that (1) New Forest streams already experience conditions that are potentially deleterious to brown trout and (2) open reaches are more susceptible to adverse thermal conditions than shaded reaches (Figure 5). We also note that higher levels of shading upstream appear to restrict the number of days that thermal thresholds for trout are exceeded (Figure 6D and E). These observations indicate the potential for riparian shade to protect streams against the effects of high temperatures. It appears that a riparian woodland cover of >80% for a 100 m to 1 km reach could, potentially, moderate maximum temperatures such that the upper limit for optimum growth of brown trout is exceeded for less than about 30 days per year (Figure 6D). Similarly, maximum temperatures could be maintained below the incipient lethal limit for brown trout with about a 40% cover of riparian woodland for an upstream reach of 100 m to 1 km (Figure 6E).

In addition to brown trout, many of the other fish species present in the New Forest are sensitive to water temperature (Table III). Although thermal tolerances derived under controlled *ex situ* conditions are not necessarily truly representative of *in situ* tolerances (Malcolm *et al.*, 2008), it is apparent that maximum stream temperatures observed in this study at many sites in the New Forest streams were sufficiently high to exceed critical thermal maxima for several fish species that are less sensitive to temperature than brown trout (Tables II and III). On the basis of published critical thermal maxima (Table III), it would appear that sites such as Markway Lawn (Table II), where maximum water temperatures have occasionally reached 34.5°C, will only remain viable for eel and chub.

Table III. Range of thermal tolerances for adult fish of the species found in Ober Water and Dockens Water. Optimum range is that over which feeding occurs and there are no external signs of abnormal behaviour; critical thermal maximum is the highest temperature tolerated with no mortality over 7 days ('incipient lethal temperature'), dependent on the experimental conditions such as the acclimation temperature and the rate of warming

Species	Optimum range (°C)	Critical thermal maximum (°C)
Brown trout <i>Salmo trutta</i> ^a	4–19	19–24
Brook Lamprey <i>Lampetra planeri</i> ^b	12	—
Bullhead <i>Cottus gobio</i> ^d	4–27	24–28
Eel <i>Anguilla anguilla</i> ^{e,f}	8–29	30–39
Minnow <i>Phoxinus phoxinus</i> ^f	13–25	23–31
Chub <i>Leuciscus cephalus</i> ^f	8–25	27–39
Pike <i>Esox Lucius</i> ^f	9–25	29–34
Stone Loach <i>Nemacheilus barbatulus</i> ^c	5–28	24–29

^aElliott, 1981; ^bMaitland, 2003; ^cElliott *et al.*, 1994; ^dElliott and Elliott, 1995; ^eSadler, 1979; ^fKüttel *et al.*, 2002.

This study has shown that expanding the cover of riparian woodland could be used as a means to moderate temperature maxima for the potential benefit of the New Forest's fish. At present, the level of riparian shade within wooded reaches in the study catchments effectively moderates stream temperatures below the incipient lethal limit for brown trout (Figure 6E). Our evaluation of riparian shade does not distinguish between deciduous and coniferous trees (Figure 1). However, water temperatures follow a repeating seasonal cycle (Figure 2) and critical thermal thresholds for brown trout tend to be exceeded only when broadleaved trees are in full leaf. There appears to be no advantage, therefore, in creating coniferous riparian woodland to provide year-round shade.

The existing spatial distribution of riparian shade reflects the 'mosaic' of habitats across the New Forest, with sizeable areas of open, unshaded 'lawns' between extended reaches of woodland providing a high level of riparian shade. The level of riparian shade within open lawns that typically extends over a distance of 1 km or more is generally less than 30% (provided by occasional riparian shrubs). The results suggest that it should be possible to maintain these important open habitats but also improve the protection for fish by targeted planting of riparian trees to achieve the desired level of shade. At the same time, habitat management for the benefit of fish should not ignore the broader needs of the New Forest's stream biota. The southern damselfly *Coenagrion mercuriale*, for example, requires channels that are open and unshaded, with abundant marginal vegetation, and their population densities may be negatively affected by riparian trees (Rouquette and Thompson, 2005). This study also highlights the need to try and retain some tree cover within the extended riparian zones of clearfelled conifer plantations until planted broadleaved trees can provide adequate shade to prevent summer temperature maxima exceeding critical thermal thresholds for fish.

Management of the New Forest should, of course, be planned in full recognition of future climate change. Increased stream temperature has been predicted as a probable consequence of climate change (Mohseni *et al.*, 1998; Ducarne, 2008) and some evidence of a warming trend has already been reported elsewhere in UK (Langan *et al.*, 2001; Durance and Ormerod, 2007). The results of this study add to evidence of the effectiveness of riparian woodland in regulating stream temperature (Malcolm *et al.*, 2008) and supports its use as a tool for climate change adaptation (Broadmeadow and Nisbet, 2004, Scottish Natural Heritage, 2004; Forestry Commission, 2006). Our findings indicate that planting new riparian woodland to achieve *ca.* 20% canopy cover along at least a 500 m reach of small, surface water dominated streams, could be effective in preventing current summer maximum water temperatures from exceeding lethal limits for salmonids and other fish. Higher levels of riparian woodland cover are likely to be needed to address future climate warming; a predicted air temperature rise of 4–5°C (Hulme *et al.*, 2002) would likely lead to thermal thresholds for fish being exceeded more frequently and for longer. Planning and implementation of tree planting to ameliorate climate change impacts on fish requires fuller understanding of the relationship between air and stream water temperatures in the context of riparian cover. A further study will elucidate this relationship for lowland streams in the New Forest, such that future planting can be targeted in catchments known to currently support salmonid fisheries, specifically at spawning sites that are presently open and exposed to direct insolation.

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