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Quantifying the effect of semi-natural riparian cover on stream temperatures: implications for salmonid habitat management

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Abstract Previous studies examining the effects of riparian cover on stream temperatures have led to highly variable findings. In an attempt to reduce these uncertainties, this study examines the relationship between stream temperature variability and local climatic conditions over discrete 300-m sections of a watercourse. Seventeen stream sections were chosen within the Slaney catchment on the basis of riparian cover and size. Continuous monitoring over a 2-year period from May 2010 found that riparian cover had a measurable cooling effect on water temperatures at small spatial scales. The magnitude of this effect was dependent on stream size and local climactic conditions.

KEYWORDS: habitat management, nursery streams, riparian shade, solar radiation, stream temperature.

Introduction

Temperature is considered a key abiotic factor affecting salmonid growth and maintenance (Preall & Ringler 1989; Lobon-Cervia & Rincon 1998; Railsback & Rose 1999). It directly affects feeding rates and growth efficiencies as well as invertebrate prey production (Johnson *et al.* 2006). In general, uptake and costs have been found to be exponential functions of temperature (Broekhusien *et al.* 1994). Therefore, relatively small changes in stream temperatures could have major effects on salmonid responses to these changes.

The complexity of the relationship between water temperature and salmonid growth is highlighted by the conflicting results found from laboratory and field-based experiments. Elliott and Hurley (1997) arrived at a well-accepted optimum temperature for growth of salmon parr, *Salmo salar* L., of 15.9 °C during laboratory experiments. However, this is considered too simplistic for natural conditions where metabolic expenditure from foraging and avoiding predators is greater than in a laboratory. During field experiments in Scotland, Jones *et al.* (2002) found maximum growth of juvenile salmonids occurred early in the season when food availability was high and temperatures and basal maintenance rates were low. Although net assimilation was just as high in the summer, growth essentially stopped because high summer temperatures implied high maintenance rates that used up all ingested food and prevented it going into structural tissue. Other theories suggest that high early season growth rates could also be attributed to compensatory growth, where organisms exhibit faster growth during periods of recovery from starvation than they do during periods of high food availability alone (Broekhusien *et al.* 1994; Yearsley *et al.* 2004).

During autumn and winter, salmonids can survive low assimilation rates due to accompanying low metabolic rates of 23–29% of that in summer (Priede 1985) and behavioural adaptations such as entering torpid states (Broekhusien *et al.* 1994). From these observations, the argument could be made that low flows and higher air temperatures, and a subsequent increase in water temperatures caused by climate change, have the potential to slow down the spring growth/recovery process when food finally becomes available again because more ingested food would be used up for maintenance and metabolism than in cooler water. Therefore, in the following starvation phase, there would be less reserve biomass to be used for maintenance. This could have huge implications for salmonid survival rates. O'Grady (1993) argued that Irish summer temperatures are not extreme and rarely approach lethal values for salmonid species.

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This is true and it is unlikely that climate change will cause this. However, while death from temperature intolerance marks complete breakdown in a fish, it is well recognised that feeding, resistance to disease (Marcogliese 2001), successful reproduction (Jonsson *et al.* 2001) and sufficient activity (Larsson & Berglund 2005) are all necessary for continued survival of the organism. Temperature affects all of these.

River water temperature is a resulting variable due to the net amount of heat inputs and outputs under specific hydraulic (stream velocity and flow) and meteorological conditions. The latter would include air temperature, solar radiation (dependant on stream aspect, depth/width ratio and shade), wind and humidity (Gu & Li 2002). Only incident solar radiation onto a streams surface can be controlled without resorting to morphological alterations of watercourses. The reduction in incident solar radiation, which is the singular most important radiant energy source for heating streams during daytime conditions (Brown & Krygier 1970; Beschta 1997; Webb & Zhang 1997; Johnson 2004), can be achieved by providing shade over streams, usually in the form of riparian vegetation. This is potentially the most cost-effective and sustainable management option to control the effects of climate change on salmonid stocks in both Irish rivers and those elsewhere in Europe. These boundaries between terrestrial and fluvial ecosystems can be vitally important in shallow salmonid nursery areas, particularly during low flows when strong sunshine can cause peak summer water temperatures to rise to dangerously high levels for salmonids (Hendry *et al.* 2003). As well as providing shade, riparian vegetation can benefit fluvial ecosystems in a number of ways. It has been reported that riparian vegetation can promote biodiversity and productivity within a stream (Naiman *et al.* 1993; Broadmeadow & Nisbett 2004). Riparian vegetation has the ability to impede rapid surface water run-off, thereby reducing the introduction of sediment to a stream (Hendry *et al.* 2003). Roots from riparian vegetation improve soil structure and as a consequence stabilise banks (Castelle *et al.* 1994). Also, woody debris and in-stream roots are likely to be more abundant in streams with overhanging vegetation, providing cover from predators and refuge from high flows (Lehane *et al.* 2002). The type of vegetation that makes up the riparian canopy also has the ability to affect the quality and quantity of allochthonous input to streams. Aquatic invertebrates prefer feeding on broadleaf litter than on conifer needles (Ormerod *et al.* 1986), and broadleaf woodland supports a more abundant and diverse stream macro-invertebrate community than both coniferous plantation and open moorland (Cowan 1998).

There is a large literature that attests to riparian cover having a major effect on stream temperature (Gray & Edington 1969; Gregory *et al.* 1987; Broadmeadow & Nisbett 2004; Boegh *et al.* 2009; Brown *et al.* 2010; Broadmeadow *et al.* 2011; Leach *et al.* 2012). Originally, riparian zones were examined to test the effects of forest clearing on riverine habitat. Swift & Messer (1971) found that forest cutting raised temperatures of small streams in the Southern Appalachians. Likewise, Binkley & Brown (1993) summarised the results from 20 North American watershed studies and found that forest harvest without leaving riparian buffers typically allowed maximum summer stream water temperatures to increase by 2–6 °C, whereas in most cases keeping riparian buffer kept the increase in maximum summer temperature to <2 °C.

In Scotland, Malcolm *et al.* (2004) found altered temperature regimes in the upper catchment of a Scottish river where riparian woodland appeared to moderate stream temperatures. The effect on cleared test sites was most marked at short diel temporal scales where high daily maximum temperatures were followed by rapid cooling at night. As the test sites in this study were typical of many upland streams, it is likely that temperature regimes such as these occur in many similar streams which are particularly responsive to solar radiation due to their small size and open aspect (Mitchell 1999). This small temporal scale effect could impinge on growth and performance of salmonid populations. Quinn & Wright-Stow (2008) found a similar effect in small streams in New Zealand, which experienced high summer maxima. However, while the larger streams did not display the same effect, they did exhibit increased summer mean temperatures compared with uncleared controls. This effect reflects slower cooling in the larger catchment at night. In the Oregon cascades in Canada, Johnson (2004) found that maximum water temperatures declined significantly in the shaded reach of a second-order stream, but minimum and mean temperatures were not modified. Stream width was also found to affect the relationship between stream temperature and riparian cover (Li *et al.* 2012).

Using riparian zones to ameliorate maximum summer stream temperatures is still quite contentious in higher latitude catchments. Some fisheries groups advocate that riparian zones should be left open to maximise water temperatures and thus salmonid productivity (Broadmeadow & Nisbett 2004). Weatherley & Ormerod (1990) reported that brown trout in a forest-cleared stream attained 97% of the mass of trout in the control vs 78% in an uncleared stream. This result was attributed to higher stream temperatures caused by the opening of the riparian zone, accelerating growth. O'Grady (1993) reached similar conclusions within larger study sites. However, other studies found that, depending on environmental circumstances, salmonids exhibited a preference for streams with heavy riparian cover (Johansen *et al.* 2005; Dineen *et al.* 2007a). These results imply that salmonid preference or otherwise for riparian cover may be site specific and it is likely that a balance between unshaded and shaded sections along a watercourse provides the most productive habitat for salmonids (Hendry *et al.* 2003).

It is likely that stream size is an important factor in determining whether or not salmonids choose streams with riparian cover. The surface area of small streams makes the relative importance of terrestrial invertebrate inputs to fish diet much higher than in large rivers (Kelly-Quinn & Bracken 1990; Johansen *et al.* 2005). Therefore, in larger streams it is possible that benthic invertebrate availability would not be limiting, and so it would not be necessary to complement diet with terrestrial invertebrates. Likewise, deeper water and more complex in-stream components would provide cover from predators so the advantages of riparian canopy would be diminished (Riley *et al.* 2009). Larger watercourses convey larger volumes of water; therefore, the temperature regulation effect of riparian cover is less apparent than in their smaller equivalents (Larson & Larson 1996; Quinn & Wright-Stow 2008). These observations suggest that if riparian buffer strips are to be used to manage stream temperatures, stream size may be a factor in the decision-making process.

In the light of these uncertain trophic effects of stream shading (Wilby *et al.* 2010), the main challenge for the future is to develop cost-effective methods that have the ability to ameliorate maximum summer-time stream temperatures while ensuring sufficient in-stream primary productivity. This could be achieved by alternating shade with open sections along streams if relatively small sections of shading could be shown to have the ability to reduce water temperatures.

Hannah *et al.* (2008), while acknowledging the work carried out on the effect of riparian cover on stream temperature, highlighted the potential confounding effects around these analyses. Shrimpton *et al.* (2000) also noted uncertainty around the moderating effects of stream temperature load. This study attempts to remove a major contributor of prospective confounding effects, namely all upstream environmental processes by focusing solely on temperature differences across discrete 300-m sections of watercourse in isolation from the rest of the catchment rather than simply analysing water temperature effects at the downstream end of a study unit.

To determine the influence of riparian cover on water temperatures over small spatial scales in two size classes of stream channel within the Slaney catchment, it was hypothesised that the presence of semi-natural riparian cover along a 300-m stretch of stream channel has the potential to cause a quantifiable effect on river water temperature due to shade from direct solar radiation. It was expected that this effect would be more apparent in smaller streams than larger ones and that the magnitude of this effect is dependent on environmental conditions. Secondly, it was hypothesised that the rates of daily water temperature increase between the upstream and downstream end of a 300-m stretch of stream channel are related to the presence of riparian cover. The magnitude of this effect would also depend on stream size, environmental conditions and season.

Methods

Study area description

Observations were made at 17 study sites in the River Slaney catchment, which is a designated Special Area of Conservation due to the presence of Atlantic salmon, as well as many other species of conservation interest. The Slaney catchment covers an area of 639 ha. The River Slaney rises in the Wicklow Mountains (E302696, N192189) and flows in a southerly direction for 117 km until it reaches the Irish Sea at Wexford, primarily through undulating lowlands. The catchment includes a considerable amount of arable and pasture land. As the underlying catchment geology is predominantly granite, slates and shales from the Devonian period, it is principally rain water recharged. Catchments of this type are particularly susceptible to high summer time water temperatures as they have little groundwater input to moderate in-stream water temperatures (Johnson 2004; Caissie 2006).

Site selection and study design

Data from 17 stream sections in the northern part of the Slaney catchment were used in this study (Fig. 1, Table 1). These 300-m-long stream sections were grouped by size (large or small) and riparian cover (shaded or unshaded) giving a total of nine shaded sections (four large, five small) and eight unshaded sections (four large, four small). A length of 300 m ensured that the proportion of riffle/glide/pool sequences was similar between sites.

Stream sections were classed as small or large based on the wetted width at six randomly chosen cross-sectional transects and mean pool depth. Large stream sections had a mean wetted width of ≥ 8 m and a mean pool depth ≥ 0.6 m. Small stream sections had a mean wetted width ≤ 4 m and a mean pool depth ≤ 0.4 m.

Stream sections were grouped into shaded and unshaded by visual assessment. Stream sections lined on both banks with trees that put the surface of the stream

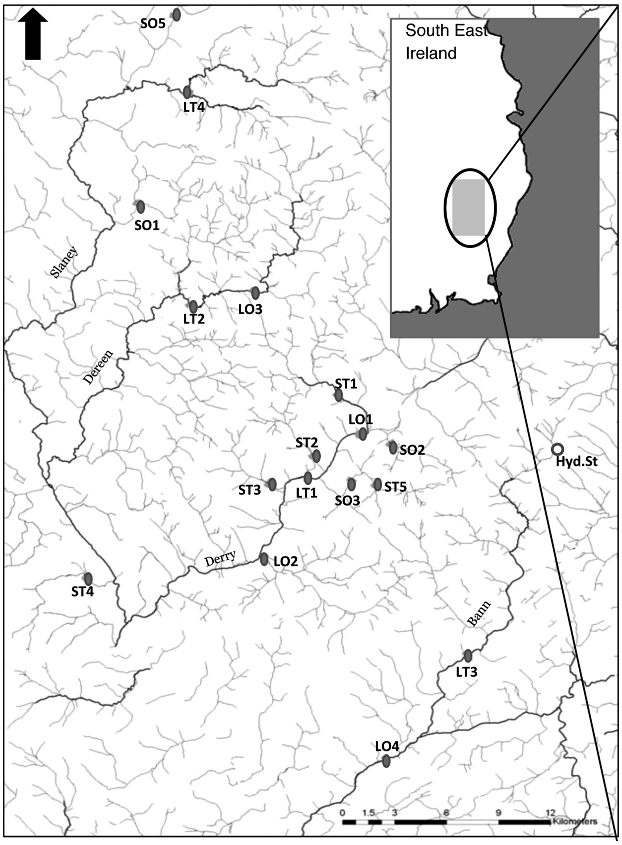

Figure 1. Study area showing sites and hydrometric station location. For site code explanations refer to Table 1.

completely in the shade were considered shaded. Stream sections with no trees on either bank were considered unshaded. The occasional small section of shade (<4 m) within a proposed unshaded channel was deemed to be insignificant for the purposes of this study. Likewise, small openings within shaded sites were allowed.

Channel orientation is known to affect the amount of short-wave radiation that can reach a stream (Malcolm *et al.* 2004). The design of this study accounted for this by ensuring that site orientation varied equally across all treatments.

Data on 30th percentile flow ($m^3\ s^{-1}$) were obtained from the EPA Hydrodata portal (http://hydronet.epa.ie/). Daily mean stream flows were calculated from estimated flows for the study sites provided in the EPA Hydrodata portal, using actual data collected by the EPA from the hydrometric station at Pallis Bridge on the River Bann (Fig. 1).

The 17 study sites were all adjacent improved agricultural grassland. The riparian corridors along the shaded sites were made up predominantly of alder, *Alnus* sp., and willow, *Salix* sp., with the remainder consisting of other native species, including holly, *Ilex sp*., hawthorn, C*rataegus* sp., blackthorn, *Prunus* sp., sycamore, *Acer* sp., and ash, *Fraxinus* sp. Tree height typically varied from 8–15 m. Riparian corridor widths rarely exceeded 1–2 trees deep. Hourly air temperature and daily sunshine hours were provided by the nearby (<30 km) meteorological stations at Clonroche and Oak Park.

Water temperature data collection

At the upstream and downstream end of each 300-m study site, water temperature was recorded at 30-min intervals using Onset Hobo Water Temp Pro v2 Data

Table 1. Study site characteristics

Site code	% Slope	30th percentile flow $m^3\ s^{-1}$	Wetted width (m)	Pool depth (cm)	Altitude (m)	Flow direction	U/S catchment (km^2)	Riparian cover
SO1	9.8	0.36	3.5	35	130	N to S	12.8	Unshaded
SO2	8.9	0.38	3.0	36	90	SE to NW	12.2	Unshaded
SO3	10.4	0.51	4.0	38	80	NE to SW	16.7	Unshaded
SO5	14	0.40	3.5	35	160	N to S	12.4	Unshaded
ST1	8.7	0.64	4.0	36	160	N to S	27.9	Shaded
ST2	11.2	0.37	3.3	25	100	N to S	14.7	Shaded
ST3	13.2	0.32	3.4	38	90	NW to SE	12.1	Shaded
ST4	9.5	0.43	3.9	26	70	NW to SE	17.4	Shaded
ST5	10.8	0.39	4.0	29	85	SE to NW	11.9	Shaded
LO1	9.7	1.4	9.0	85	80	E to W	55.5	Unshaded
LO2	8	1.3	8.0	95	60	E to W	61.7	Unshaded
LO3	10.1	2.3	11	110	140	E to W	59.7	Unshaded
LO4	8.9	3.4	11	110	50	NE to SW	143.5	Unshaded
LT1	10.3	2.5	13	85	70	E to W	103.8	Shaded
LT2	9.4	2.7	11	92	110	SE to NW	71	Shaded
LT3	9.7	2.2	10	78	50	NE to SW	93.5	Shaded
LT4	16.6	2.5	10	90	150	N to S	47.7	Shaded

Loggers. The 30-min interval between measurements ensured that all relevant diel fluctuations were detected. All loggers were initially cross-calibrated over a range 0–25 °C and then secured to the riverbed inside a PVC pipe to shield the logger from direct sunlight. Gaps in the time series data occurred due to data loggers being washed away during flood events or because data were excluded from loggers that were buried in the sediment or exposed to air.

The analysis focussed on the months from June to August in 2010 and 2011 (referred to as summer10 and summer11 respectively) because stream temperatures at this time of the year are most likely to have an effect on salmonids. Table 2 provides a summary of the prevailing weather conditions during these two summers. Table 3 provides a summary of the water temperature characteristics of the various site types over the two summers.

For each day during summer10 and summer11, the time of day (t_{MAX}) when the downstream water temperature was at its daily maximum was identified. For the analysis, the upstream temperature (*TEMP_US*) was extracted for each day at t_{MAX} and the temperature differential across the 300-m section (*TEMP_DIFF* = downstream temperature minus upstream temperature) was calculated. The final analysis used data from 1906 time points.

Statistical analysis

The effects of riparian cover (*COVER*) and stream size (*SIZE*) on the water temperature differential over the 300-m stream sections were modelled using a linear mixed-effect model (Pinheiro & Bates 2000). Additional variables (Table 4) were included in the model to control for confounding effects. The temporal autocorrelation in the errors was described by an ARMA(p,q) process, and the response variable, *Y*, was a power transformation of *TEMP_DIFF* ($Y = \mathit{TEMP\_DIFF}^{0.2}$) to ensure normal residual errors. The final model included main effects and two-way interactions of all the variables. Variation between study sites was accounted for by a random effect of *SITE* on the intercept. The inclusion of upstream temperature (*US_TEMP*) as a covariate in the analyses was important to control for confounding effects, although it was not necessary to analyse actual upstream temperature values in the context of this study.

The model was fitted by maximum likelihood using the nlme package in R (Pinheiro *et al.* 2012; R Core Team 2012), temporal autocorrelation was visualised using the autocorrelation function of the residuals and *P*-values were calculated by sequentially applying Wald

Table 2. Mean climatic conditions during the two study periods (standard deviations shown in brackets)

	Daily max air temperature (°C)	Daily rainfall (mm day^{-1})	Daily sunshine (h day^{-1})	Daily flow (m^3 sec^{-1})
Summer10	19.5 (1.6)	2.3 (4.7)	6.1 (4.0)	0.24 (0.20)
Summer11	18.1 (2.3)	2.2 (3.6)	5.3 (3.8)	0.17 (0.07)

Table 3. Summary statistics calculated from 30-min water temperature data collected from the upstream ends of study sites

	Treatment	Small /Unshaded	Small /Shaded	Large /Unshaded	Large /Shaded
Summer 10	Mean	13.8	13.61	14.47	14.74
	Maximum	18.35	16.95	18.41	18.79
	Minimum	8.6	8.48	9.59	9.95
Summer 11	Mean	13.04	12.71	13.91	13.91
	Maximum	17.56	16.56	18.59	19.04
	Minimum	8.85	7.74	9.58	9.53

Table 4. The nine explanatory variables used in the linear mixed model. The response variable is *TEMP_DIFF*$^{0.2}$. SITE was a random effect on the intercept and *DAY* was used for the ARMA error structure. The rest of the model contained linear effects of all continuous variables and their interaction with discrete variables. All continuous variables were scaled to have zero mean and unit variance

Variables	Mean (SD)	Units	Description
Continuous			
TEMP_DIFF	0.29 (0.32)	°C	The difference between upstream and downstream water temperature when downstream water temperature was at its daily maximum
TEMP_US	14.9 (1.4)	°C	Upstream water temperature when downstream water temperature was at its daily maximum
FLOW	0.46 (0.62)	m^3 sec^{-1}	Estimate daily mean flow in the stream section
SUN	5.6 (3.9)	h day^{-1}	Daily number of hours of sunshine
AIRTEMP	18.9 (2.8)	°C	Maximum daily air temperature
Discrete			
SIZE	small/large		Size of the stream section (see main text)
COVER	shaded /unshaded		Riparian cover along the stream section
YEAR	2010/2011		Year of data collection
SITE			Identity of the stream section (see Table 1)
Time			
DAY		Days	The number of days since the study began

tests. Terms involving *SIZE* and *COVER* were tested last to control for the other variables.

Mean diel variability

Temperature data were collected every 30 min at the upstream and downstream ends of each study site. To illustrate diel in-stream temperature profiles within the four categories of stream section (differing in size and riparian cover) at both ends of the study sites, the data recorded at each particular time increment for each day during both summers were grouped and averaged independently of one another. This was performed separately for each of the four stream types. For clarity, these data sets were divided into subsets according to air temperature achieved in a day. Three separate air temperature increments were created (16–18 °C, 18–20 °C and 20–25 °C) for each of the four stream types.

Results

The temporal autocorrelation in the residuals was adequately described by a first-order moving average term (ARMA process with $P = 0$, $q = 1$) with a parameter $\theta = 0.19$ (where the residual at time t is $\varepsilon_t + \theta\ \varepsilon_{t-1}$ and ε_t is a normally distributed error). The variation in the model's intercept between sites was estimated to have a standard deviation of 0.05, compared with the residual standard deviation of 0.08 (Table 5).

The temperature differential across all 300-m stream sections varied significantly with year ($P < 0.001$), sunshine ($P < 0.001$), flow ($P = 0.001$) and upstream water temperature ($P < 0.001$, Table 5). The temperature differential was larger in summer11 than summer10 (Fig. 2), although this difference was less for high upstream temperatures ($P < 0.001$). Increasing sunshine generally increased the temperature differential (Figs 3–6), but this effect was weakened by increasing flow ($P < 0.001$) and increasing upstream temperature ($P = 0.03$). Decreasing flow also increased temperature differentials in small stream sections but not in large stream sections. The effect of upstream water temperature varied between years and between categories of riparian cover. No effect of air temperature could be detected once the effects of upstream temperature, sunshine, flow and year had been accounted for.

After taking account of all confounding variables, a significant effect of riparian cover remained ($P < 0.001$), such that temperature differentials were lower in shaded stream sections (Fig. 7, Table 5). The effect of riparian cover was greatest in summer11 ($P = 0.002$) and increased with increasing sunshine ($P < 0.001$). The effect of sunshine in increasing temperature differential

Table 5. The linear mixed-effects model output for the response variable *TEMP_DIFF*$^{0.2}$ using an ARMA(0,1) error structure and fitted using maximum likelihood. Variables are described in Table 3, all continuous variables have been centred and scaled, and interactions are denoted by a colon. The intercept corresponds to *COVER* = Unshaded, *SIZE* = small, *YEAR* = 2010, *FLOW* = 0.16 m^3 s^{-1}, *TEMP_US* = 15.5 °C, *SUN* = 6.1 h and *AIRTEMP* = 19.5 °C. *P*-values are from sequential Wald tests

	Coefficient	SE	d.f.	*F*	*P*-value
Intercept	**0.783**	**0.028**	**1728**	**2800**	**<0.001**
TEMP_US	**0.031**	**0.007**	**1728**	**76**	**<0.001**
(YEAR = 2011)	**0.044**	**0.010**	**1728**	**54**	**<0.001**
SUN	**0.040**	**0.004**	**1728**	**248**	**<0.001**
FLOW	**−0.097**	**0.015**	**1728**	**11**	**0.001**
AIRTEMP	−0.011	0.007	1728	0.36	0.55
TEMP_US : (YEAR = 2011)	**−0.032**	**0.007**	**1728**	**21**	**<0.001**
TEMP_US : SUN	**−0.013**	**0.003**	**1728**	**4.7**	**0.03**
TEMP_US : FLOW	**−0.007**	**0.006**	**1728**	**18**	**<0.001**
TEMP_US : AIRTEMP	0.001	0.003	1728	0.95	0.33
(Year = 2011) : SUN	−0.003	0.004	1728	<0.01	0.95
(Year = 2011) : FLOW	0.002	0.008	1728	1.7	0.19
(Year = 2011) : AIRTEMP	**0.022**	**0.009**	**1728**	**13**	**<0.001**
FLOW : SUN	**−0.002**	**0.001**	**1728**	**36**	**<0.001**
SUN : AIRTEMP	0.001	0.001	1728	2.1	0.14
FLOW : AIRTEMP	−0.003	0.005	1728	1.5	0.21
(SIZE = Large)	**−0.080**	**0.039**	**13**	**7.4**	**0.02**
(SIZE = Large) : TEMP_US	0.008	0.009	1728	<0.01	0.99
(SIZE = Large) : (YEAR = 2011)	−0.010	0.015	1728	3.2	0.08
(SIZE = Large) : SUN	−0.004	0.006	1728	2.8	0.09
(SIZE = Large) : FLOW	**0.093**	**0.015**	**1728**	**46**	**<0.001**
(SIZE = Large) : AIRTEMP	−0.004	0.008	1728	<0.01	0.99
(COVER = Shaded)	**−0.216**	**0.036**	**13**	**53**	**<0.001**
(COVER = Shaded) : TEMP_US	**−0.031**	**0.007**	**1728**	**44**	**<0.001**
(COVER = Shaded) : (YEAR = 2011)	**−0.030**	**0.010**	**1728**	**10**	**0.002**
(COVER = Shaded) : SUN	**−0.017**	**0.005**	**1728**	**17**	**<0.001**
(COVER = Shaded) : FLOW	0.006	0.005	1728	1.9	0.16
(COVER = Shaded) : AIRTEMP	−0.005	0.006	1728	0.8	0.36
(COVER = Shaded) : (SIZE = Large)	0.075	0.053	13	1.9	0.19

Terms with a $P < 0.05$ are highlighted in bold. The ARMA(0,1) parameter estimate for the moving average is $\theta = 0.19$, and standard deviation associated with *SITE* = 0.05, leaving the residual standard deviation = 0.08.

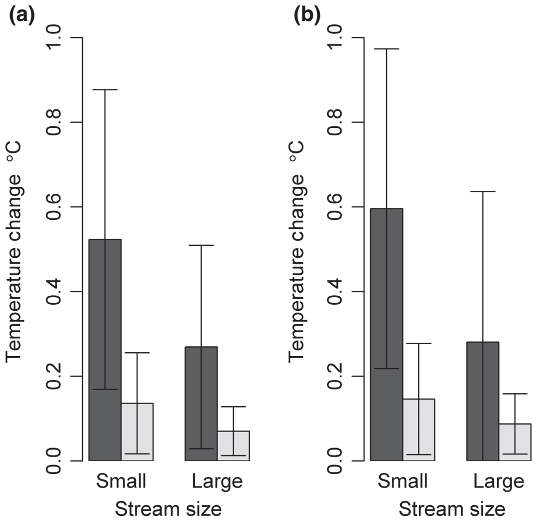

Figure 2. Effect of YEAR mean temperature differential in small and large stream sections when YEAR = 2010 (a) and 2011 (b) Open and filled bars correspond to shaded and unshaded riparian cover, respectively. Error bars represent 1 standard deviation.

was weaker, but still present for shaded stream sections ($P < 0.001$, Figs 3–6).

Large stream sections were also found to have lower temperature differentials than small stream sections ($P = 0.02$, Fig. 7), but the effect of stream size was reduced at higher flow rates ($P < 0.001$). No interaction between stream size and level of riparian cover was detected.

Variations in stream warming within sites were reflected in average stream temperature profiles over a period of 24 h. As soon as stream warming began in the morning, water temperatures tended to diverge gradually between the upstream and downstream ends of small unshaded study sites during the day, until the daily maximum temperature differential within the study sites was achieved, prior to reconverging as the night approached. This divergence was not clear within the small shaded sites (Fig. 8a–c) or within the large sites (Fig. 9a–c). Temperature differences during winter and early spring were observed to be much lower than at other times of the year (November to April; Fig. 10).

Discussion

This study examines the local, fine spatial scale effects of riparian buffer strips on the summer time water temperatures within salmonid nursery streams. The results provide evidence that short strips (300 m) of semi-natural riparian buffer can cool small nursery streams by up to 1 °C, depending on environmental factors. A large proportion of this effect can be attributed to stream surface shading from solar radiation as the model developed described a strong interaction between riparian cover and solar radiation, measured in this instance as sunshine hours.

These observations demonstrate that the effect of localised factors can be important to stream temperature changes at spatial scales of 100s of metres. This

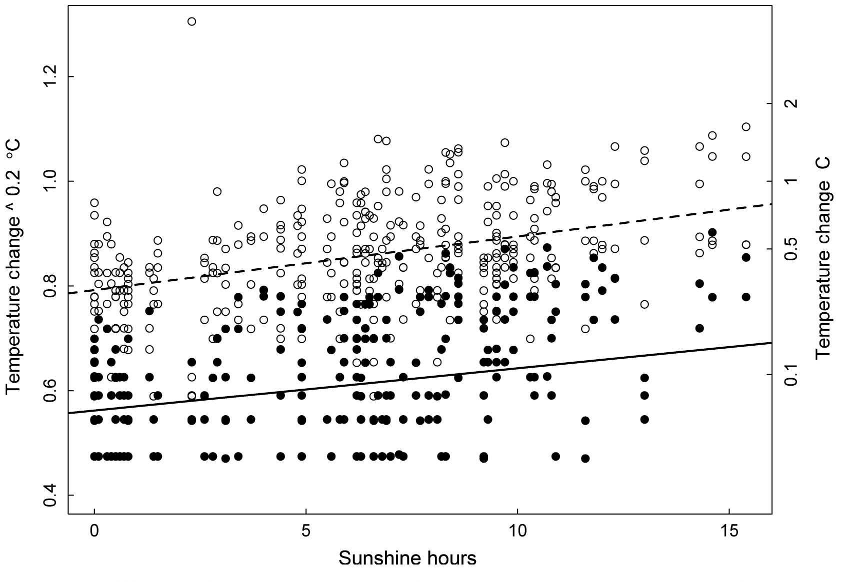

Figure 3. The observed temperature differential for small, shaded sites (filled symbols) and small, unshaded sites (open symbols) in summer10 as a function of sunshine hours and riparian cover. Solid and dashed lines represent the model's best fit line for shaded and unshaded sites respectively. The left-hand *y*-axis is *TEMP_DIFF*$^{0.2}$ and the right-hand *y*-axis is a non-linear scale for *TEMP_DIFF*.

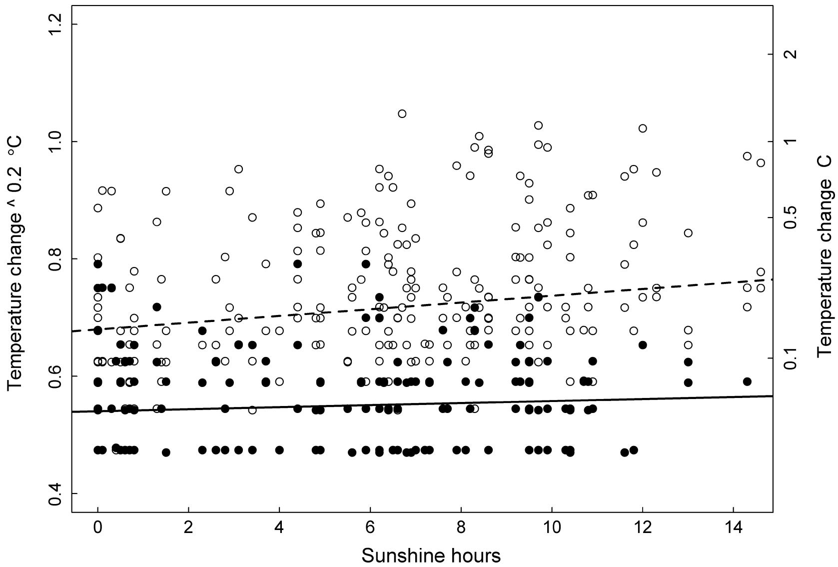

Figure 4. The observed temperature differential for large, shaded sites (filled symbols) and small, unshaded sites (open symbols) in summer10 as a function of sunshine hours and riparian cover. The details are the same as for Fig. 3.

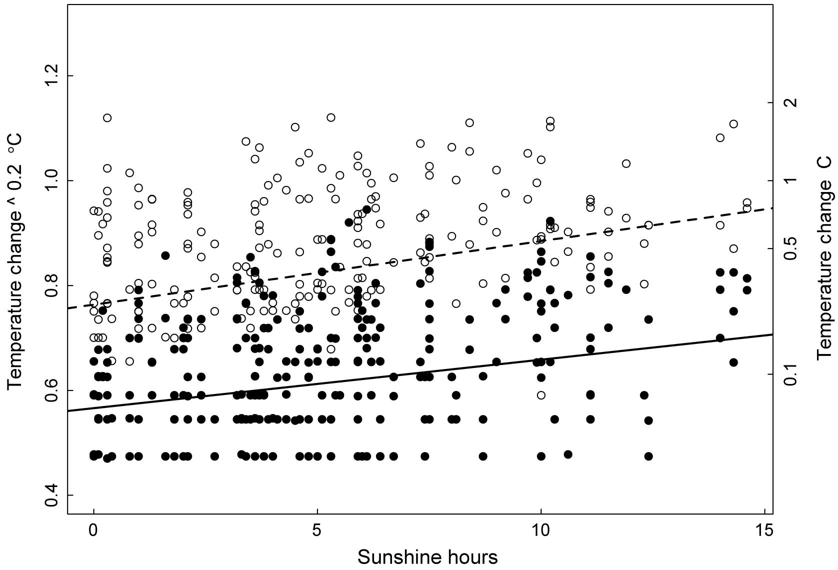

Figure 5. The observed temperature differential for small, shaded sites (filled symbols) and small, unshaded sites (open symbols) in summer11 as a function of sunshine hours and riparian cover. The details are the same as for Fig. 3.

conclusion is consistent with observations in Wales (Weatherley & Ormerod 1990), Scotland (Malcolm *et al.* 2004), North America (Moore *et al.* 2005) and New Zealand (Rowe & Pearce 1994), where unshaded streams in generally unshaded catchments were compared against those with riparian cover. However, the aforementioned studies observed warmer stream temperatures in generally unshaded catchments (over several kilometres or more) than their shaded counterparts. The present study showed that the effect of riparian cover on stream temperatures can also be observed at much smaller scales.

This study is also consistent with conclusions made by Hannah *et al.* (2008), which stated that incoming short-wave radiation is one of the major components of stream energy budgets. The presence of riparian buffer at relatively small scales appears to reduce the effect of short-wave radiation, measured as sunshine hours. It has been predicted that average seasonal temperatures will increase by 0.75–1.0 °C by 2020, and by the 2050s it is predicted that Irish air temperatures will increase by 1.8 °C (Fealy & Sweeney 2009). This result provides evidence for the utilisation of riparian buffer to mitigate

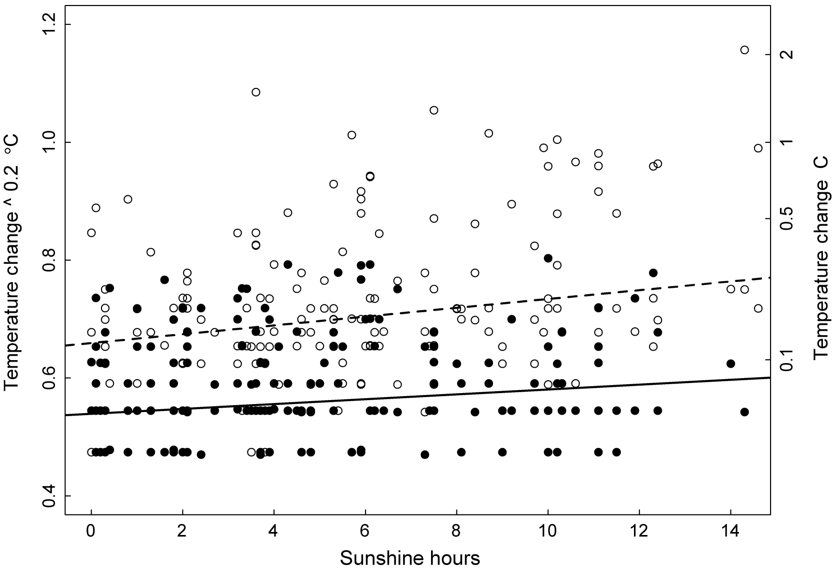

Figure 6. The observed temperature differential for large, shaded sites (filled symbols) and small, unshaded sites (open symbols) in summer11 as a function of sunshine hours and riparian cover. The details are the same as for Fig. 3.

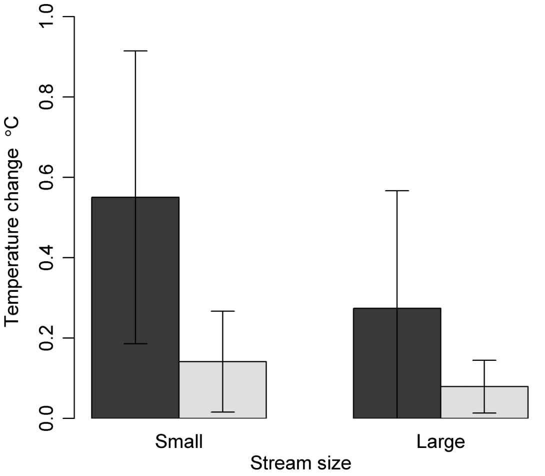

Figure 7. The mean temperature differential, *TEMP_DIFF*, in small and large stream sections. Open and filled bars correspond to shaded and unshaded riparian cover, respectively. Error bars represent 1 standard deviation.

for increased stream temperatures that are likely to occur as a consequence of a warming climate.

Stream flow was found to have an effect on temperature increases within sites during summer 2010. However, because the Slaney is a surface water-dominated system, high stream flows did not tend to persist and fluctuated quite rapidly, therefore, the validity of these effects could be open to question, although stream flow is known to affect stream warming (Malcolm *et al.* 2004). It was also found that high stream flows dampened the ability of sunshine to warm streams. This is not surprising as higher stream flows would mean that there is more water within the study site to heat per unit time and that water would move through the site at a quicker rate, meaning less time for sunshine to warm it. These conclusions have implications from a river management perspective. Charlton & Moore (2003) inferred likely changes in effective run-off in Irish rivers due to global climate change. They concluded that all areas are likely to experience a decrease in summer run-off, with greatest reductions in the east of Ireland, where this study took place. The specific effect of decreased rainfall on flows is determined by the catchment storage capacity of the stream in question. In catchments with high infiltration rates, and thus large storage capacities, the impacts of summer droughts are likely to be less severe. However, surface run-off-dominated catchments, such as the Slaney catchment are likely to experience greater impacts in summer due to prolonged low flows (Murphy & Charlton 2008). The conclusions reached in this study highlight the potential for increased summertime stream warming in surface water-dominated catchments lacking riparian buffer.

All streams were similar in terms of surrounding land use, geology, size, flow and altitude. However, natural systems, by their nature, meant it was difficult to select stream sections that were identical in all respects apart from riparian cover. Any differences were accounted by including additional variables within the final model. Upstream temperature (the model variable *US_Temp*) was included to control for any potential confounding effects upstream of the study sites.

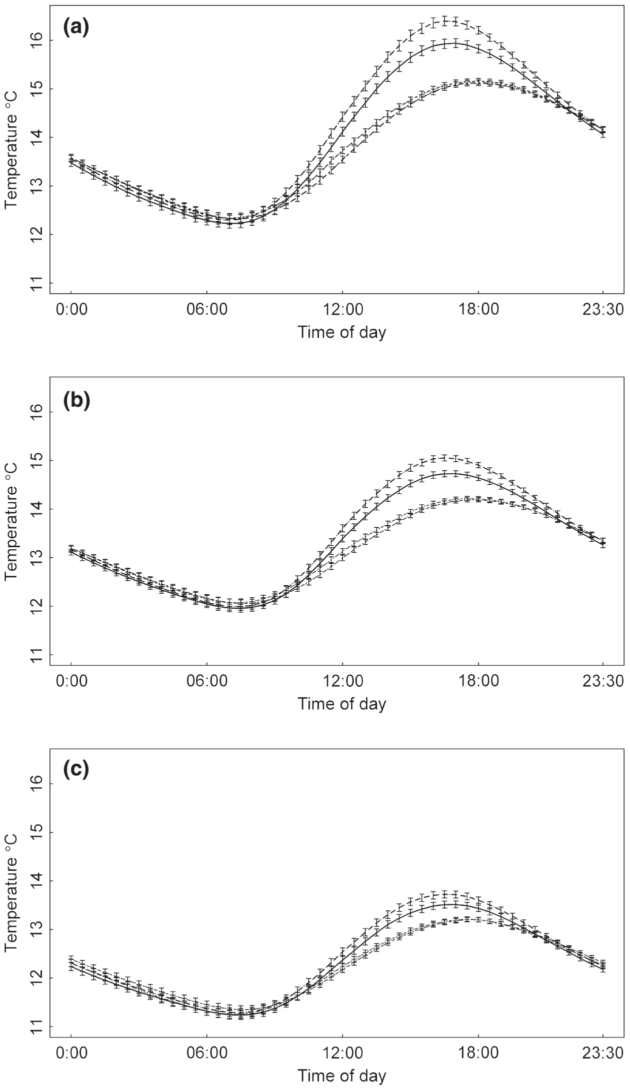

Figure 8. Mean (± SE) diel temperature regimes for small sites over both summers when daily maximum air temperatures are (a) 20–25 °C, (b) 18–20 °C and (c) 16–18 °C for unshaded-upstream (solid line), unshaded-downstream (dashed line), shaded-upstream (dotted line) and shaded-downstream (dotted-dashed line) water temperatures.

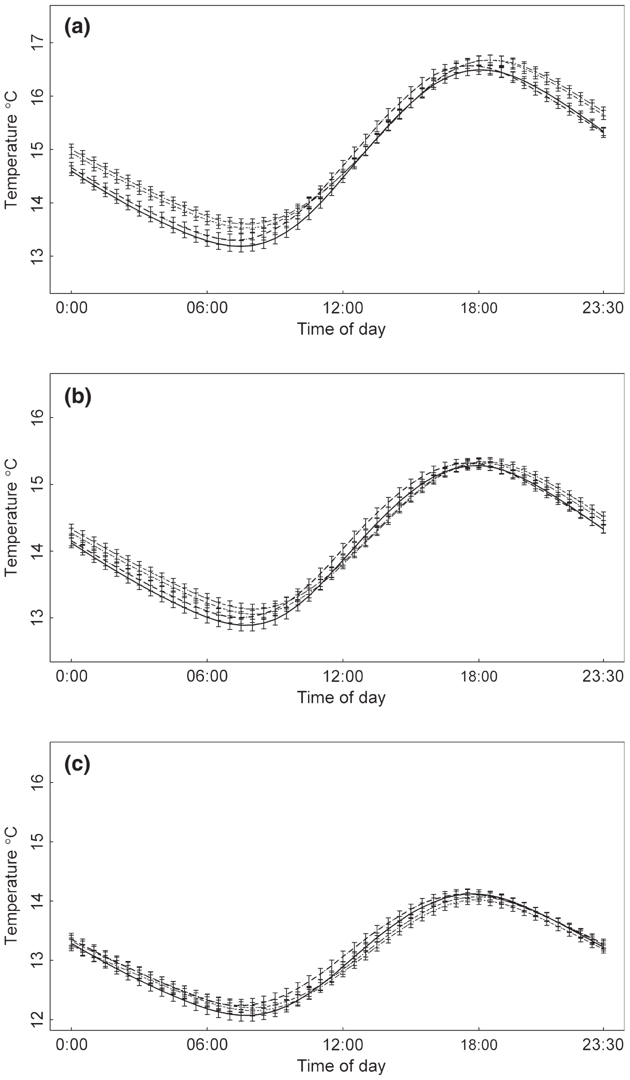

Figure 9. Mean diel temperature regimes for large sites over both summers when daily maximum air temperatures are (a) 20–25 °C, (b) 18–20 °C and (c) 16–18 °C for unshaded-upstream (solid line), unshaded-downstream (dashed line), shaded-upstream (dotted line) and shaded-downstream (dotted-dashed line) water temperatures.

In summer time, it could be expected that the growth of macrophytes would be more prominent in unshaded sites than in the shaded ones (McCormick & Harrison 2011). Occasionally quite significant stands were present within some sites by the end of the summer. For example, one of the small unshaded sites had as much as 25% of its surface covered by macrophytes (mainly *Ranunculus* sp.) towards the end of the summer (data not presented). Although this was considered to be an unavoidable natural process intrinsically linked to unshaded sites only, some effect on water temperature is likely. Roth *et al.* (2010) noted a cooling effect due to in-stream vegetation within trapezoidal stream channels in Belgium. However, from observations on the study sites it was considered that in-stream vegetation may also impede the transition of water through study channels and thus maximise the opportunity for warming. With reference to this, it was noted that summer time increases were slightly greater in small unshaded sites in Summer11, although air temperatures and sunshine hours were lower than in summer 2010. Larger vegetation stands within the small unshaded streams were noted in summer11. It was likely that this was due to the lower average stream flows during summer 2011. Lower in-stream flows would increase the likelihood that in-stream vegetation is given greater

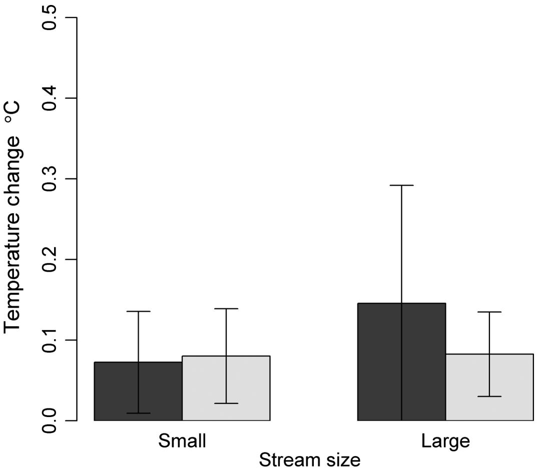

Figure 10. The mean temperature differential, *TEMP_DIFF*, in small and large stream sections from November 1st 2010 until March 31st 2011. Open and filled bars correspond to shaded and unshaded riparian cover, respectively. Error bars represent 1 standard deviation.

opportunity to persist and ultimately thrive in this habitat. It was hypothesised that extra vegetation coupled with the lower flows of summer 2011 would mean greater residence times of water within sections of channel thereby giving more time for water to be warmed by short-wave radiation as it moves through the study site. However, further work must be carried out to confirm this.

Even under present climatic conditions, riparian cover greatly reduces the potential for salmonids to become thermally stressed. Webb & Crisp (2006) found that even in the uplands of south-west Scotland, which would have a similar climate to Ireland, temperatures in the upper critical range for brown trout, *Salmo trutta* L. ($\geq$ 19 °C), were recorded in an unshaded stream for 150 h over 4 years, whereas at the shaded site, maximum temperatures never exceeded 16 °C. In this study, diel variation in stream temperature increases was found to be far more pronounced in unshaded streams over very small spatial scales (300 m). This variation in stream temperatures can be expected to have an effect on salmonid growth as it varies non-linearly with temperature (Elliott & Hurley 1997). These effects have the potential to affect not only salmonid survival but also to influence salmonid growth through all stages of the salmonid life cycle. As well as the free swimming part of the life cycle, earlier stages are controlled by temperature. For example, the incubation period for salmonid eggs is directly dependant on water temperature: at 3 °C the incubation period is around 145 days, whereas incubation is about 40 days at 10–12 °C (Drummond Sedgwick 1982). Warmer temperatures in the latter stage of incubation (early spring) may therefore produce smaller and less fit alevins (Marten 1992). This early emergence has the potential to expose these alevins to peak flood and extreme flow conditions in spring in the future, as predicted by Murphy & Charlton (2008), thus putting increasing physiological demands on them. These early emergers may also have limited food availability as their emergence may become uncoupled with the emergence of invertebrates, their primary prey (Curry *et al.* 1993). However, this study found no differences in stream temperature changes due to riparian cover during the winter and early spring months. As this is the part of the year when salmonid incubation occurs, riparian cover would not be expected to affect salmonid emergence times.

This study found that small patches of riparian cover have a noticeable effect on stream temperatures regardless of stream size. It also established that the low thermal capacity of the small sites compared with their large equivalents meant greater overall temperature increases in small unshaded sites than their large counterparts, as per work by Webb *et al.* (2003). So if there was a particular focus on buffering small sections of low-order nursery streams within a catchment, it is likely that the moderating effects of this would be transmitted downstream due to the high latent heat capacity of water (Shrimpton *et al.* 2000). Smaller tributaries with lowered energy budgets would ultimately assimilate into larger channels within the catchment and thereby lower the overall temperatures achieved in the larger channels of the catchment. As larger channels are not as susceptible to warming from short-wave radiation due to a lower surface area than the lower ordered streams, the promotion of riparian buffer to reduce summer maximum temperatures along large channels may be unnecessary provided the low-order streams of the catchment have been managed to reduce energy inputs in the form of direct sunlight. However, from the results obtained in this study, it cannot be said how much of the upper reaches of a catchment must be shaded to lower an elevated water temperature in the lower part of the catchment. Further research which examines the rate of stream rewarming when a low-order stream moves from a shaded section to an unshaded section would be very useful in this context.

Riparian canopy may be effective in lowering summer water temperatures. However, the literature provides conflicting evidence regarding salmonid preference for shaded sites. When salmonids are found in higher numbers in open canopy sites, this is attributed to increase in primary productivity in the stream. Some authors believe this leads to an increase in macro-invertebrate prey for the salmonids (Lester *et al.* 1994). Others suggest that it is the ability of large macrophytes to grow in the stream, and hence provide in-stream cover for salmonids in open channels (Eklov & Greenberg 1998). There are many inconsistent data relating to the abundance of macroinvertebrates in a stream in relation to the level of riparian vegetation. It has been hypothesised that the presence of riparian canopy is preferable because it causes greater variation in groups of invertebrates in the water column due to the presence of terrestrial and aerial species and may mean that there is less competition for prey between different age classes and species of salmonids (Dineen *et al.* 2007b). A large-scale study in Northern Norway by Johansen *et al.* (2005) found that salmon parr tended to migrate upstream from spawning grounds to presumably more suitable habitat. They concluded that this habitat was associated with dense riparian vegetation that complemented diet with terrestrial invertebrates. There is a need to resolve any uncertainties relating to effects of riparian shading on salmonid production and their diet.

Nevertheless, the observations highlighted in this study confirm that small 300-m sections of riparian buffer have a measurable effect on stream temperature. Therefore, it may be possible to promote the growth of riparian buffer interspersed within open sections of channel to reduce overall energy inputs while reducing the risk of a detrimental loss in primary productivity (O'Grady 1993). However, further investigations are required to define the actual proportion of shading required over low-order streams that would be necessary to lower overall water temperatures within catchments, while ensuring that there are no detrimental impacts on salmonid productivity (O'Grady 1993).

It has been promoted as good practice to allow the development of riparian buffers along streams flowing through agricultural land under the Rural Environment Protection Scheme (REPS) (Emerson & Gillmor 1999). However, at present, there is no legislation in Ireland to compel landowners to do this. In reality it is difficult to convince landowners that using up valuable land for bankside vegetation is a worthwhile cause. It is likely that the promotion of short patches of riparian buffer which do not exceed 1–2 trees deep followed by open sections along nursery streams flowing through agricultural land would be more acceptable to landowners, than long unbroken riparian buffer zones, because their introduction would cause minimal loss of agricultural land.

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