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Inter-annual variability in the effects of riparian woodland on micro-climate, energy exchanges and water temperature of an upland Scottish stream

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Abstract:

The influence of riparian woodland on stream temperature, micro-climate and energy exchange was investigated over seven calendar years. Continuous data were collected from two reaches of the Girnock Burn (a tributary of the Aberdeenshire Dee, Scotland) with contrasting land use characteristics: (1) semi-natural riparian forest and (2) open moorland. In the moorland reach, wind speed and energy fluxes (especially net radiation, latent heat and sensible heat) varied considerably between years because of variable riparian micro-climate coupled strongly to prevailing meteorological conditions. In the forested reach, riparian vegetation sheltered the stream from meteorological conditions that produced a moderated micro-climate and thus energy exchange conditions, which were relatively stable between years. Net energy gains (losses) in spring and summer (autumn and winter) were typically greater in the moorland than the forest. However, when particularly high latent heat loss or low net radiation gain occurred in the moorland, net energy gain (loss) was less than that in the forest during the spring and summer (autumn and winter) months. Spring and summer water temperature was typically cooler in the forest and characterised by less inter-annual variability due to reduced, more inter-annually stable energy gain in the forested reach. The effect of riparian vegetation on autumn and winter water temperature dynamics was less clear because of the confounding effects of reach-scale inflows of thermally stable groundwater in the moorland reach, which strongly influenced the local heat budget. These findings provide new insights as to the hydrometeorological conditions under which semi-natural riparian forest may be effective in mitigating river thermal variability, notably peaks, under present and future climates. © 2014 The Authors. *Hydrological Processes* published by John Wiley & Sons Ltd.

KEY WORDS stream/river temperature; inter-annual variability; riparian forest; stream energy budget; hydrometeorology; climate change mitigation

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INTRODUCTION

Thermal dynamics in streams are driven by energy and hydrological fluxes at the air–water and water–riverbed interfaces (Gu and Li, 2002; Hannah *et al.*, 2004; Malcolm *et al.*, 2004a) and may be modified by land and water management (Poole and Berman, 2001; Webb *et al.*, 2003; Webb and Nobilis, 2007; Hannah *et al.*, 2008). A changing climate, linked to elevated greenhouse gas concentrations, is expected to yield increased long-wave radiation flux from the atmosphere and consequently elevated air temperatures (Wild *et al.*, 1997), increased sensible heat fluxes from the atmosphere (Leach and Moore, 2010) and elevated groundwater temperatures

(Meisner *et al.*, 1988; Leach and Moore, 2010). Hence, there is growing concern that a changing climate may be associated with increases in stream temperature (Langan *et al.*, 2001; Hari *et al.*, 2006; Durance and Ormerod, 2007; Webb and Nobilis, 2007; Huguet *et al.*, 2008; Kaushal *et al.*, 2010; van Vliet *et al.*, 2011), which may have profound impacts on physical, chemical and biological processes in flowing waters (Poole and Berman, 2001; Caissie, 2006; Webb *et al.*, 2008) and consequently on freshwater ecosystems (Webb and Walsh, 2004; Wilby *et al.*, 2010).

Stream energy budgets are driven primarily by diurnal and seasonal variability in solar radiation (Beschta *et al.*, 1987). Thus, shading at the stream surface by riparian vegetation represents one potential measure for mitigating thermal variability and extremes (Malcolm *et al.*, 2004a; Moore *et al.*, 2005a; Gomi *et al.*, 2006; Hannah *et al.*, 2008; Imholt *et al.* 2010; 2012). In North America, ‘best’ management practice is to protect streams against direct

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STUDY AREA AND SITES

insolation using wooded riparian buffer strips (Zwieniecki and Newton, 1999; Young, 2000; Moore *et al.*, 2005a.). In the UK, the Forest and Water Guidelines recommend the provision of shading by native woodland where salmonids prevail (Forestry Commission, 2011). However, despite riparian forest being advocated as an effective way to mitigate river temperature (notably extremes), there is limited process-based evidence to support such recommendations because research to date has often been as follows: (1) short-term (i.e. less than two calendar years Hannah *et al.*, 2008) and (2) focused primarily on the effects of forest harvesting on summer maximum temperatures (Malcolm *et al.*, 2008).

The authors are unaware of any previous studies that provide a process-based understanding of inter-annual variability in seasonal stream temperatures as they relate to riparian micro-climate and energy exchange. Johnson and Jones (2000) investigated water temperature variability in a coniferous forest catchment and two clear-cut catchments in the western Cascades, Oregon, over a 6-year period. They observed that weekly maximum summer water temperatures varied by up to 1 °C under forest cover and up to 4 °C in clear-cuts between years. Differences between shaded and un-shaded sites were greatest during periods of high solar radiation gain and lower during periods of high cloud cover (i.e. low solar radiation gain). This suggests that micro-climate and energy exchange conditions may control water temperature variability and extremes in forested reaches, perhaps because the micro-climate of un-shaded riparian zones is coupled more strongly to prevailing climatic conditions, as observed by Guenther *et al.* (2012).

To address the aforementioned research gaps, this paper compares stream temperature, riparian micro-climate and energy exchange dynamics between a moorland (no trees) reach and a semi-natural forested reach in the Scottish Cairngorms over seven calendar years. The study aimed to improve understanding of the conditions and processes that affect the magnitude of the forestry influence (as indicated by inter-site differences in temperature) between years. Specifically, the following hypotheses are tested:

1. Inter-annual variability in micro-climate, net energy exchange and stream temperature is greater in the moorland than under forest cover.
2. Inter-annual variability in micro-climate and associated net energy exchange is of greater relative importance than the forest effect in determining the extent of between-reach differences in stream temperature.
3. Inter-annual variability in net energy exchange in the moorland reach is driven by energy fluxes coupled strongly to prevailing meteorological conditions, whereas a more stable micro-climate under the forest canopy weakens the influence of prevailing meteorological conditions.

The study catchment, Glen Girmock, is located in a semi-natural, upland basin that drains into the Aberdeenshire Dee, northeast Scotland (Figure 1). The altitude of the catchment ranges from 230 to 862 m, covering 30.3 km². Land use is dominated by heather (*Calluna*) moorland although areas of commercial and semi-natural forest are present in the lower catchment composed of birch (*Betula*), Scots pine (*Pinus*), alder (*Alnus*) and willow (*Salix*) (Imholt *et al.*, 2012). Study reaches were established with contrasting riparian cover: (1) heather moorland (no trees) and (2) semi-natural woodland. Sites had no tributary inflows and similar geomorphology (i.e. gravel–cobble riffles). Sediment calibre was similar between reaches, with a median particle size (D_{50}) of ~21 mm and a mean fines content (particles < 1 mm diameter) of ~5% (Moir, 1999). The geology of the Girmock catchment is dominated by granite at higher elevations and schists at lower elevations, both of which have poor aquifer properties; groundwater movement is mainly by fracture flow (Tetzlaff *et al.*, 2007). Groundwater–surface water interactions are described by Malcolm *et al.* (2005) and provide background to interpret the influence of such interactions on stream heat exchange and temperature. In brief, hyporheic conditions in the forest reach were characterised predominantly by downwelling surface water, whereas those in the moorland reach were influenced by longer residence groundwater contributions with a greater thermal stability. The moorland and forest reaches had a respective elevation of 310 and 230 m, catchment area of 20.7 and 31.0 km², mean channel bankfull width of 9.5 and 7.6 m and channel gradient of 0.01 and 0.02 m m⁻¹.

Inter-annual variability in stream temperature, microclimate and energy exchange was investigated using observations from two identical automatic weather stations (AWSs), one in each reach. AWSs were micro-sited to reduce risk of damage by ice and debris transported at high flow, and where the channel water was mixed well. In the moorland reach, the AWS was located on a lateral bar/riffle feature beyond a pool. Previous studies of hydrochemistry and hydraulic head conducted immediately upstream of this site indicate that groundwater discharge dominates; however, discharge patterns are highly spatially and temporally variable (Malcolm *et al.*, 2004b; Malcolm *et al.*, 2010). Therefore, larger scale catchment controls are considered more influential on controlling groundwater–surface water interactions than localised channel morphology in the moorland reach. In the forest reach, the AWS was located on a lateral bar as it transitions into a riffle. Previous studies of hyporheic hydrochemistry at this site have shown that it is dominated by surface water exchange (Malcolm *et al.*, 2005) with no evidence of any substantial groundwater discharge.

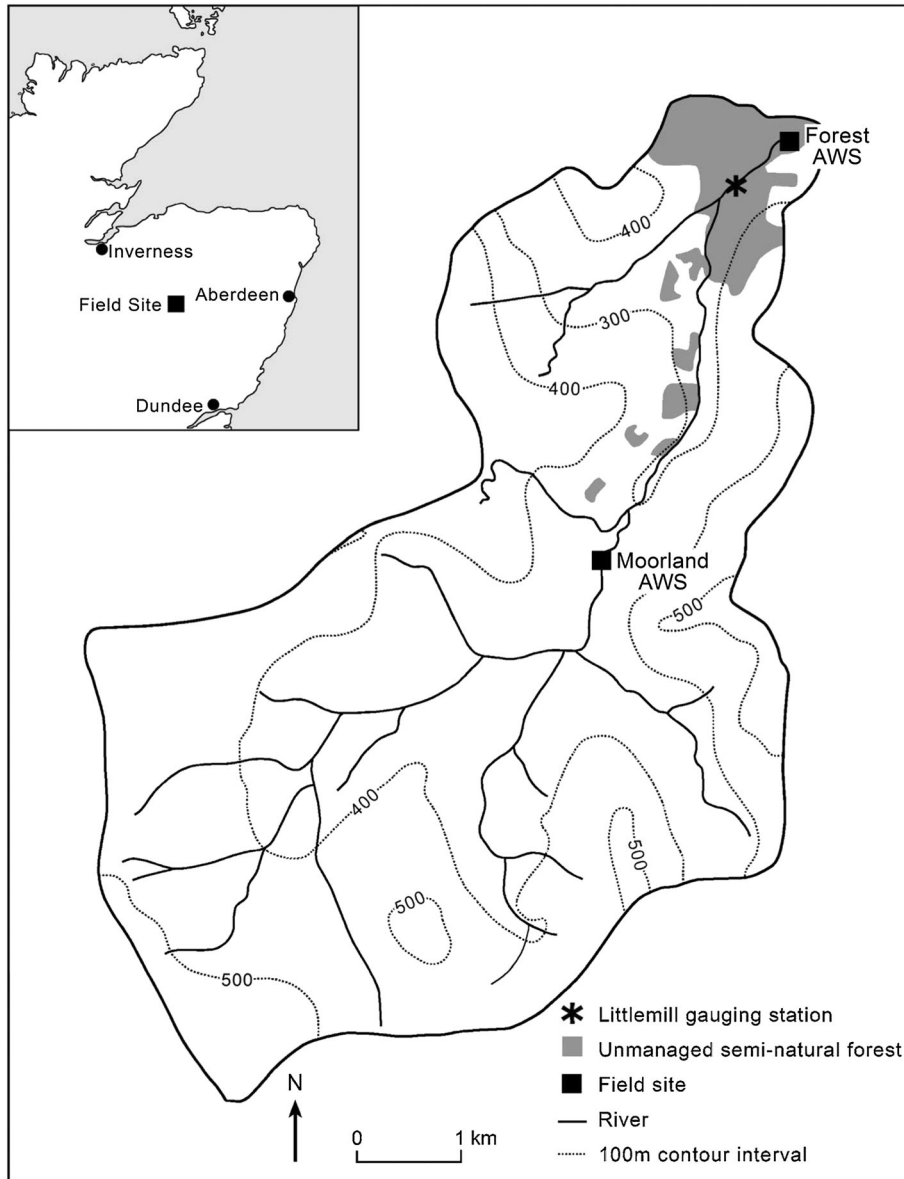


Figure 1. Location map of the Girmock Burn

DATA AND METHODOLOGY

Data collection

Data were collected across seven calendar years between 1 January 2003 and 31 December 2009. All sensors were cross-calibrated prior to installation and correction factors applied if required. Sensors were sampled at 10-s intervals, with averages logged every 15 min. Measured hydrometeorological variables included air temperature and water column temperature ($^{\circ}\text{C}$), relative humidity (%), wind speed (ms^{-1}), net radiation and bed heat flux (Wm^{-2}) (Table I). Meteorological measurements were made ~ 2 m above the stream surface in each reach. The bed heat flux plate and thermistor (for water temperature measurement)

were located directly below each AWS. The heat flux plate was buried at 0.05-m depth to avoid radiative and convective errors. The heat flux plate provided aggregated measurements of convective, conductive and radiative heat exchanges between the atmosphere and the riverbed, and the riverbed and the water column (Hannah *et al.*, 2008).

Low river flow during February 2006, July and August 2003 and September 2004 resulted in extended periods of dewatering within the moorland reach; thus, these data were omitted from analysis. During 2006, sensors submerged within the water column and riverbed at the moorland reach were moved further into the channel to reduce potential for dewatering. Reach-scale differences in surface water temperature within the Girmock catchment

Table I. Variables monitored and instruments employed in hydrometeorological field data collection

Variable	Instrument	Location	Instrument error
Air temperature	Campbell HMP35AC temperature and humidity probe	~ 2 m above water surface	0.2 °C
Water column temperature	Campbell 107 thermistor	0.05 m above stream bed	0.2 °C
Net radiation	NR lite net radiometer	~ 1.75 m above water surface	5%
Bed heat flux	Hukseflux HFP01 SC soil heat flux plate	0.05 m below stream bed	3%
Relative humidity	Campbell HMP35AC temperature and humidity probe	~ 2 m above water surface	1–3%
Wind speed	Vector A100R 3-cup anemometer	~ 2 m above water surface	0.25 ms ⁻¹

are insignificant (Imholt *et al.*, 2013); thus, fine scale (metres) relocation of the sensors was not considered to affect the homogeneity of observations. Datalogger failure caused a gap in observations for the moorland reach in March 2006; thus, this month was omitted from analysis.

Estimation of stream energy balance components

The energy budget of a stream reach without tributary inflows may be quantified as (Webb and Zhang, 1997; Hannah *et al.*, 2008):

$$Q_n = Q^* + Q_e + Q_h + Q_{bhf} \quad (1)$$

where Q_n is total energy available to heat or cool the water column, Q^* is net radiation, Q_e is latent heat, Q_h is sensible heat and Q_{bhf} is bed heat flux. Because the focus of the paper is to understand inter-annual variability in vertical exchanges of energy between the stream and its environment, Equation (1) does not include the effects of advective heat transfers associated with groundwater discharge and hyporheic exchange and the divergence of the longitudinal advective heat flux. Furthermore, energy derived from precipitation (after Evans *et al.*, 1998), biological and chemical processes (after Webb and Zhang, 1997) were assumed to be negligible. Following the method of Theurer *et al.* (1984), calculations for heat from fluid friction at the riverbed and banks indicated mean values in the range of 0.04–0.81 MJm⁻²d⁻¹ and 0.07–1.4 MJm⁻²d⁻¹ in the moorland and forest stream reaches, respectively. Thus, frictional heating was considered to be negligible and omitted, as is in previous studies (e.g. Moore *et al.*, 2005b; Caissie *et al.*, 2007; Hannah *et al.*, 2008; Hebert *et al.*, 2011; Leach and Moore, 2011; MacDonald *et al.*, 2014).

Latent (Q_e) and sensible (Q_h) heat were estimated and not measured (after Webb and Zhang, 1997). Latent heat (Wm⁻²) was calculated using a Penman-style equation to derive heat lost by evaporation or gain by condensation (Equation (2)).

$$Q_e = 285.9(0.132 + 0.143*U)(e_a - e_w) \quad (2)$$

where U is wind speed (ms⁻¹) and e_a and e_w are vapour pressures of air and water (kPa), respectively.

Vapour pressures were calculated as a function of air or water temperature (T) (K) after Stull (2000) (Equation (3)).

$$e_{sat}(T) = 0.611 * \exp \left[\frac{2.5 * 10^6}{461} * \left(\frac{1}{273.2} - \frac{1}{T} \right) \right] \quad (3)$$

Vapour pressure of water (e_w) was assumed to be equal to $e_{sat}(T_w)$. Vapour pressure of air was calculated using Equation (4).

$$e_a = \frac{RH}{100} e_{sat}(T_a) \quad (4)$$

Sensible heat (Wm⁻²) was calculated as a function of Q_e (Equation (5)) and Bowen ratio (β) (Equation (6)), where P is air pressure (kPa).

$$Q_h = Q_e * \beta \quad (5)$$

$$\beta = 0.66 * \left(\frac{P}{1000} \right) * [(T_w - T_a) / (e_a - e_w)] \quad (6)$$

Herein, energy fluxes are considered positive (negative) when directed toward (away from) the water column, and daily flux totals are reported in MJm⁻²d⁻¹.

Data analysis

To place the current study in a broader climatic context, air temperature and precipitation during the 7-year study period are compared with 50-year means measured at the Balmoral monitoring station (<10 km from both reaches) (UK Meteorological Office, 2014).

For analyses of the AWS data, stream temperature and riparian micro-climate, variables are presented as monthly means, whereas energy fluxes are presented as monthly means of daily totals. Detailed methodologies appropriate to test the three hypotheses are provided in detail as follows.

Hypothesis 1

Mean monthly values were calculated for each site, month and year over the 7-year period to quantify inter-annual

variability in stream temperature, micro-climate and energy exchanges. An Ansari–Bradley test (Hollander and Wolfe, 1999) was used to investigate equality of variance between sites for each calendar month to test the null hypothesis that there was no significant difference in inter-annual variability between sites. *p* values were presented as false discovery rates (Benjamini and Hochberg, 1995) to account for multiple comparisons. The Ansari–Bradley test is a non-parametric test for differences in scale between two groups and makes no distributional assumptions. For each site and month, data were centred about the mean. Linear trends across years were removed prior to analysis to remove the variance associated with temporal trends.

Hypothesis 2

Difference plots (moorland minus forest) were used to illustrate the magnitude of between-reach differences in micro-climate, net energy exchange and stream temperature. Positive (negative) observations indicated that moorland values were higher (lower) than those in the forest. Between-reach differences (in any month) were considered significant where they exceeded the root of the sum of squares in the uncertainty of the accuracy of observations (uncertainty associated with each instrument is provided in Table I) of each measurement in any calculation (Meyer, 1975). Difference plots also identified the nature of between-reach differences in each variable (i.e. moorland values typically greater than forest or *vice versa*). For months in which atypical between-reach differences occurred, it was informative to attribute the cause to conditions in the moorland or forest. Thus, the

difference was calculated between observations in these months and the 7-year mean for the reach and calendar month in which they occurred (long-term mean). The cause of atypical between-reach conditions was therefore attributed to the reach in which deviation from the long-term mean was greatest.

Hypothesis 3

The total energy available to heat or cool the stream was partitioned into heat sources and sinks (i.e. Q^* , Q_e , Q_h and Q_{bhf}) to identify the drivers of inter-annual variability in the energy budget of each reach. For months in which between-reach differences in net energy were atypical (Hypothesis 2), the difference was calculated between observations of energy balance components in these months and the 7-year mean for the component, reach and calendar month in which they occurred (long-term mean). Significant differences were identified as described for Hypothesis 2. The drivers of atypical conditions were attributed to the energy flux in the reach in which deviation from the long-term mean was greatest.

RESULTS

Results are presented in three sections: (1) characterisation of the study period within a longer-term climatic context, (2) inter-annual variability in water column temperature, riparian micro-climate and net energy exchange (sum of all fluxes in Equation (1)) both at, and between, reaches (Hypotheses 1 and 2), and (3) hydrometeorological drivers of inter-annual variability in net energy exchange (Hypothesis 3).

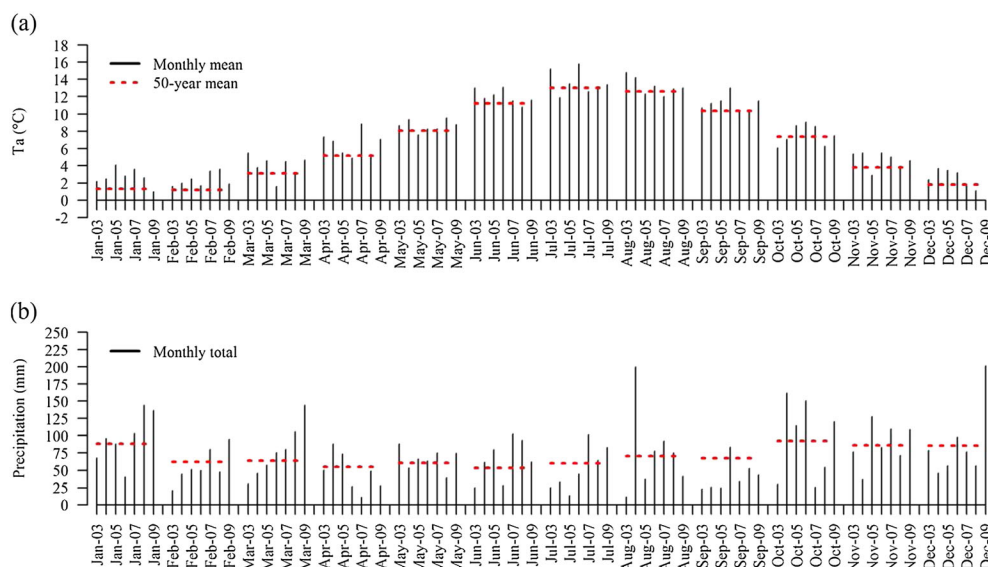


Figure 2. Monthly mean air temperature (a) and precipitation (b) at Balmoral compared to 50-year means

Table II. Variances of centred monthly means of water temperature and riparian micro-climate variables for (a) moorland, (b) forest and (c) *p* values as false discovery rates for Ansari–Bradley tests

Variable	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
<i>T_w</i> (°C)	0.29	0.23	2.58	1.62	0.93	0.85	2.57	1.43	0.64	2.27	0.36	0.27
<i>T_a</i> (°C)	0.80	0.60	2.88	1.50	0.63	0.63	2.05	0.46	0.65	2.04	0.56	2.22
<i>e_a</i> (mbar)	0.01	0.12	0.46	0.48	0.31	0.98	3.78	1.11	0.55	0.93	0.04	0.03
<i>U</i> (ms ⁻¹)	0.28	0.23	0.06	0.12	0.08	0.12	0.04	0.05	0.12	0.26	0.17	0.29

Variable	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
<i>T_w</i> (°C)	0.37	0.30	1.09	1.42	0.39	0.23	1.04	0.28	0.44	1.55	0.28	0.23
<i>T_a</i> (°C)	1.07	0.40	1.67	1.95	0.54	0.63	1.71	0.40	0.53	1.39	0.62	1.64
<i>e_a</i> (mbar)	0.13	0.03	0.44	0.82	0.25	0.17	2.59	0.45	1.35	0.79	0.10	0.09
<i>U</i> (ms ⁻¹)	0.03	0.01	0.01	0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.01	0.01	0.01

Variable	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
<i>T_w</i> (°C)	0.60	0.38	0.60	0.60	0.03	0.03	0.03	0.03	0.43	0.53	0.25	0.46
<i>T_a</i> (°C)	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70
<i>e_a</i> (mbar)	0.94	0.12	0.60	0.67	0.60	0.60	0.60	0.46	0.60	0.60	0.89	0.96
<i>U</i> (ms ⁻¹)	0.03	0.02	0.06	0.03	0.02	0.03	0.03	0.03	0.03	0.03	0.06	0.02

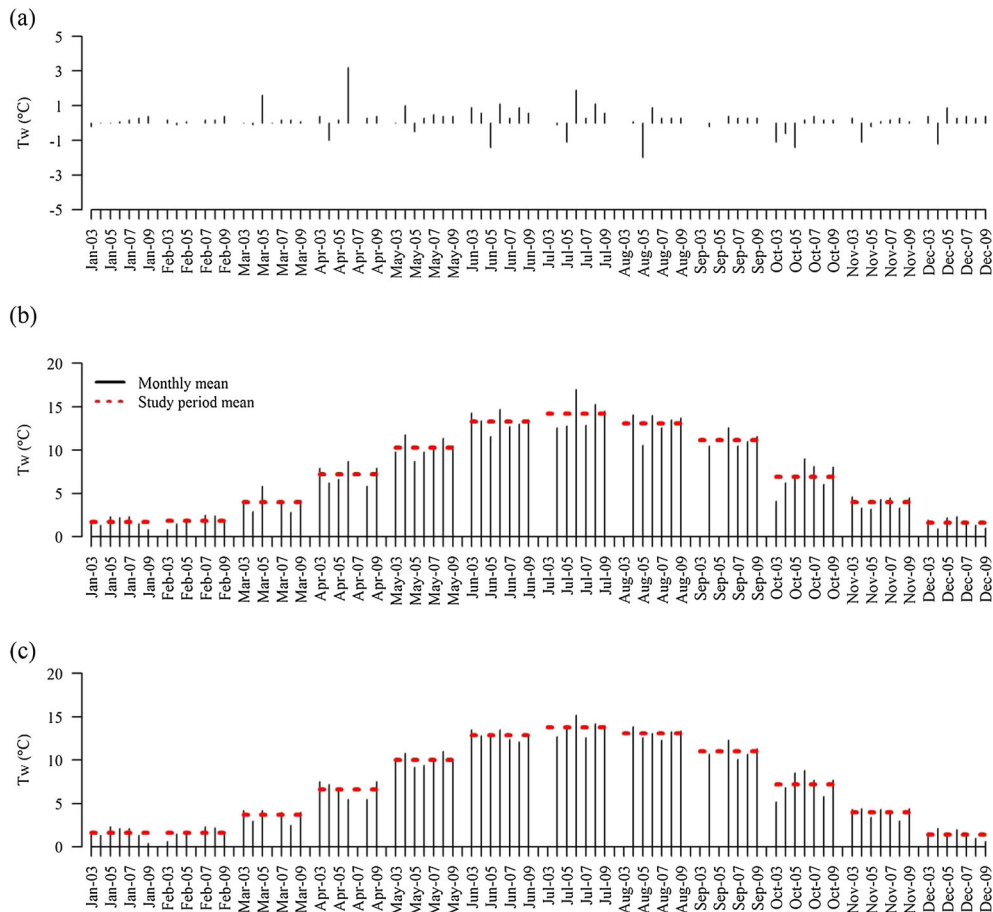


Figure 3. Monthly average water temperature: (a) moorland minus forest difference, (b) moorland, and (c) forest

Climatic context

In comparison to the previous 50 years, the climate of the 7-year study period was typically warm and dry. Air

temperature was, on average, 1.2 °C greater than 50-year means in >75% of months studied. Precipitation totals were, on average, 27.6 mm less than the means of

50-year totals in >50% of months during the study period (Figure 2).

Quantification of inter-annual variability within and between reaches

Water column temperature. Variances of mean monthly water column temperatures (Table II) were typically greater in the moorland reach than in the forest, indicating that water temperature in the moorland varied more between years than in the forest. Differences were significantly greater in the moorland between May and August, indicating that water temperature in the moorland varied more between years than in the forest.

There was substantial within and between-year variability in the magnitude of differences in monthly mean water column temperature between the forest and moorland reaches (Figure 3). During spring and summer months, between-reach differences ranged from -2.0 to $+3.2$ °C, where positive numbers indicate the moorland was characterised by higher temperatures than the forest (Figure 3). Although there was considerable variability between months and years, differences were generally positive with the exception of April 2004, May, June, July and August 2005.

During these months and years, water temperature in the moorland was consistently less than the long-term means, whereas water temperature in the forest reach was more similar to long-term conditions (Figure 3).

Between-reach differences in monthly mean water column temperature were smaller in autumn and winter months (cf. spring and summer), ranging from -1.4 to $+0.9$ °C (Figure 3). Mean monthly water column temperature in the moorland reach exceeded water temperature in the forest during most months with the exception of October 2003 and 2005, and November and December 2004. During these months, water temperatures in the moorland and forest reaches exhibited similar variability about long-term means (Figure 3). During October 2003 (2005), water temperature in both reaches was lower (higher) than the long-term mean. However, in November 2004 and 2005, the mean forest water temperature was greater than the long-term mean, whereas the moorland water temperature was closer to the long-term mean.

Riparian micro-climate. Mean monthly wind speed varied significantly more between years in the moorland than the forest. Mean monthly wind speed in the moorland was

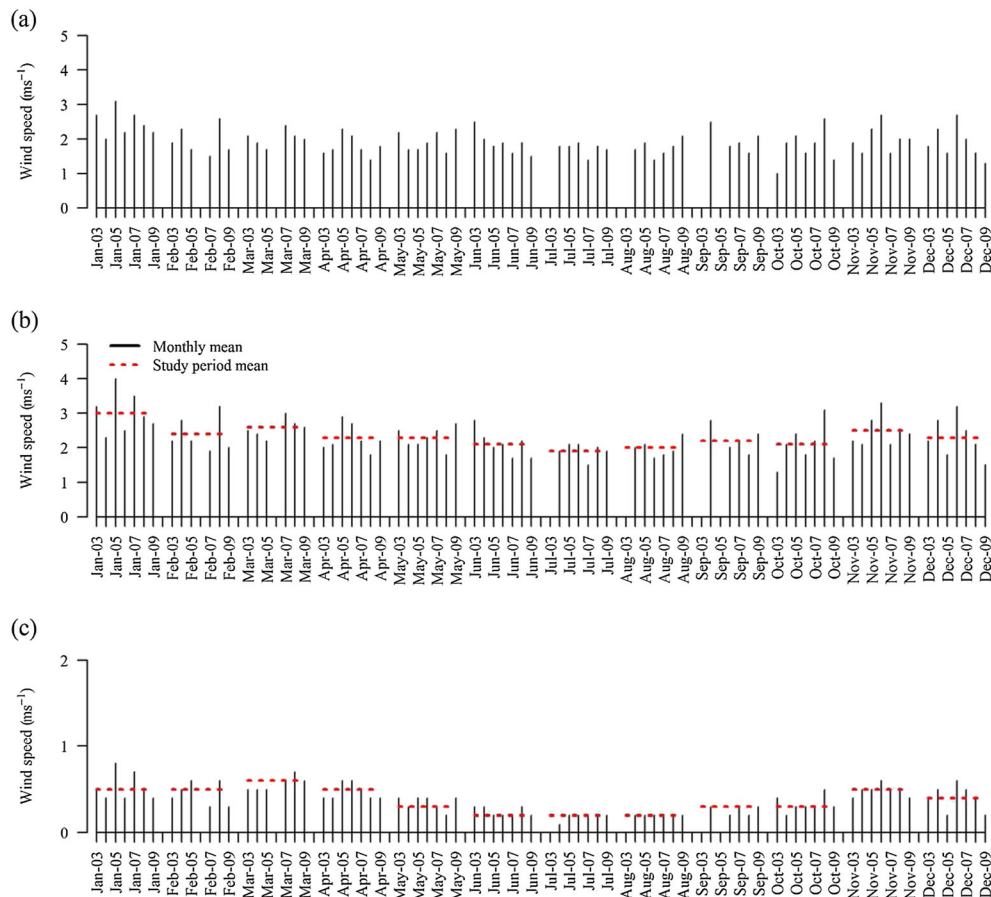


Figure 4. Monthly average wind speed: (a) moorland minus forest difference, (b) moorland, and (c) forest

always greater than that in the forest, with moorland minus forest differences ranging from 0.96 to 3.11 ms⁻¹ (Figure 4).

Between-reach differences in the variances mean that monthly air temperature and vapour pressure (an absolute measure of moisture in the air; Hannah *et al.*, 2008) were insignificant, indicating that both reaches displayed similar inter-annual variability (Table II). Mean monthly air temperature (Figure 5) and vapour pressure (Figure 6) were generally greater in the forest reach with between-reach differences in air temperature and vapour pressure ranging from -1.67 to +1.82 °C and 2.09 to 1.96 mbar, respectively.

Net energy exchange. Net energy indicates the amount of energy available to heat or cool the water column at each reach (after Equation (1)). Variances of monthly means of daily net energy totals were consistently greater in the moorland compared with those in the forest and significantly greater between May and September (Table III). Thus, net energy totals varied more between years in the moorland than the forest.

During spring and summer months, the water column received consistent net energy gains (Figure 7). Differences in monthly means of daily net energy totals ranged from -1.2 to +3.1 MJm⁻²d⁻¹ (moorland minus forest, Figure 7).

Net energy in the forest reach only exceeded that in the moorland during May 2003, 2006 and 2007, and June 2003, 2004 and 2006. During these months (excluding June 2006), net energy gain in the moorland was considerably less than long-term means, whereas net energy gain in the forest was typically closer to long-term means.

The water column typically received net energy gains during the early autumn (September), but net energy losses between October and February. Between-reach differences in autumn and winter months were smaller than those during spring and summer months, ranging from -1.3 to +1.9 MJm⁻²d⁻¹. The mean monthly net energy total in the moorland was generally less than in the forest, with the exceptions of February 2007 and 2008; October 2004, 2005 and 2006; November 2004 and 2005; and December 2004 and 2005. During these months, net energy loss in the moorland was typically considerably less than long-term means. In contrast, net energy loss in the forest was more comparable with the long-term means (Figure 7).

Drivers of inter-annual variability in net energy exchange

Net energy totals were partitioned into energy sources and sinks to determine the energy exchange processes

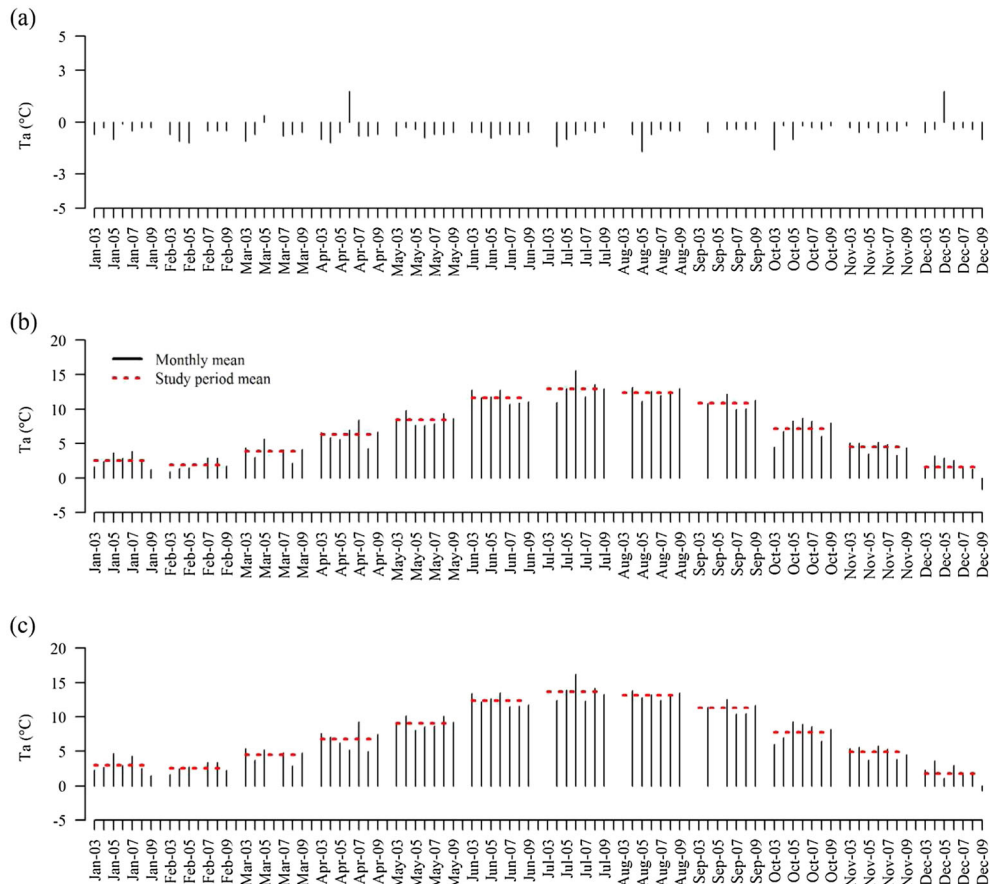


Figure 5. Monthly average air temperature: (a) moorland minus forest difference, (b) moorland, and (c) forest

INTER-ANNUAL VARIABILITY OF THE FOREST EFFECT ON STREAM TEMPERATURE

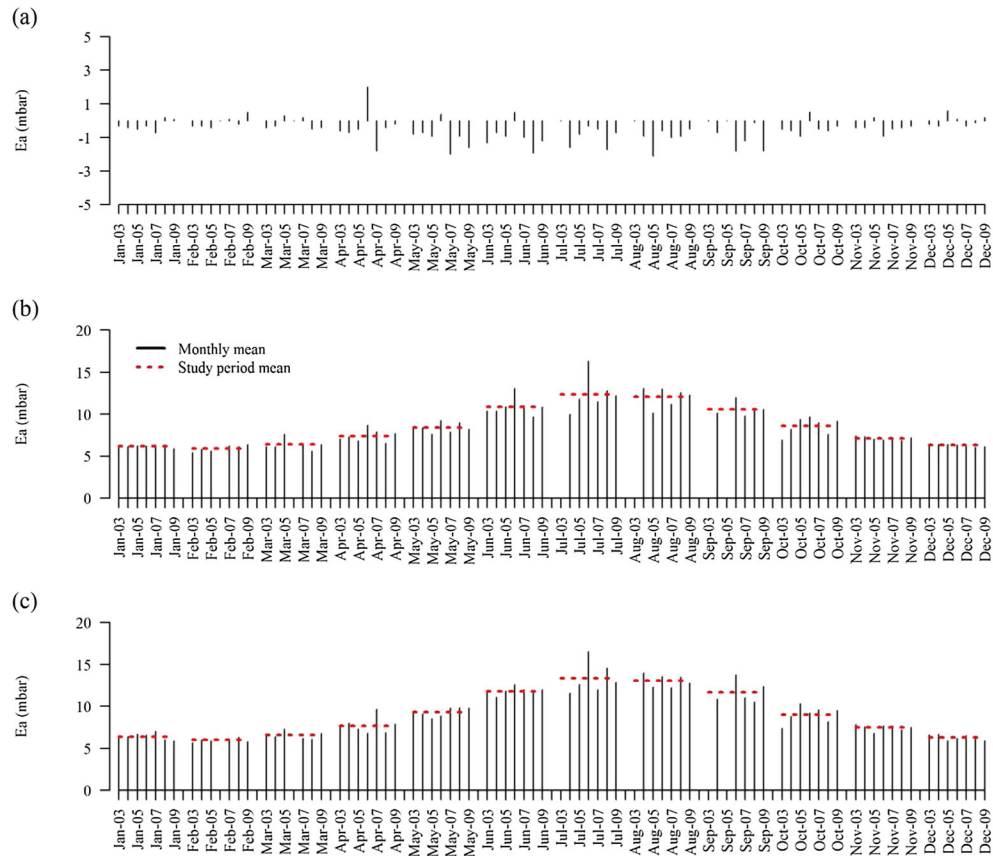


Figure 6. Monthly average vapour pressure: (a) moorland minus forest difference, (b) moorland, (c) forest

Table III. Variances of centred monthly means of daily total energy fluxes ($\text{MJm}^{-2}\text{d}^{-1}$) for (a) moorland and (b) forest, and (c) p values as false discovery rates for Ansari–Bradley tests

(a)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Variable												
Q^*	0.10	0.17	0.13	1.82	2.70	1.12	1.24	0.20	0.47	0.06	0.02	0.11
Q_e	0.04	0.04	0.14	0.47	1.30	2.76	0.63	0.20	0.11	0.29	0.09	0.06
Q_h	0.10	0.17	0.05	0.04	0.06	0.20	0.11	0.09	0.05	0.15	0.13	0.13
Q_{bhf}	0.02	0.06	0.04	0.05	0.05	0.02	0.01	0.06	0.01	0.02	0.06	0.05
Q_n	0.01	0.16	0.32	0.48	0.88	1.89	2.23	0.79	0.12	0.55	0.37	0.81
(b)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Variable												
Q^*	0.10	0.17	0.13	0.03	0.19	0.15	0.13	0.02	<0.01	0.06	0.02	0.11
Q_e	0.01	0.01	0.02	0.03	0.06	0.06	0.08	0.06	0.06	0.04	0.01	0.01
Q_h	0.04	0.01	0.01	<0.01	<0.01	0.01	0.01	<0.01	0.01	0.01	0.01	0.02
Q_{bhf}	0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.01	0.01	<0.01	<0.01	<0.01	<0.01
Q_n	0.03	0.06	0.06	0.09	0.14	0.15	0.19	0.01	0.07	0.12	0.11	0.09
(c)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Variable												
Q^*	0.18	0.24	0.30	0.01	0.01	0.03	0.05	0.03	0.32	0.03	0.03	0.24
Q_e	0.08	0.03	0.03	0.03	0.01	0.01	0.01	0.03	0.16	0.18	0.03	0.80
Q_h	0.12	0.05	0.05	0.05	0.05	0.22	0.05	0.05	0.05	0.05	0.08	0.16
Q_{bhf}	0.01	0.02	0.03	0.04	0.02	0.02	0.03	0.06	0.02	0.02	0.02	0.02
Q_n	0.70	0.15	0.15	0.01	0.01	0.05	0.04	0.01	0.05	0.22	0.70	0.06

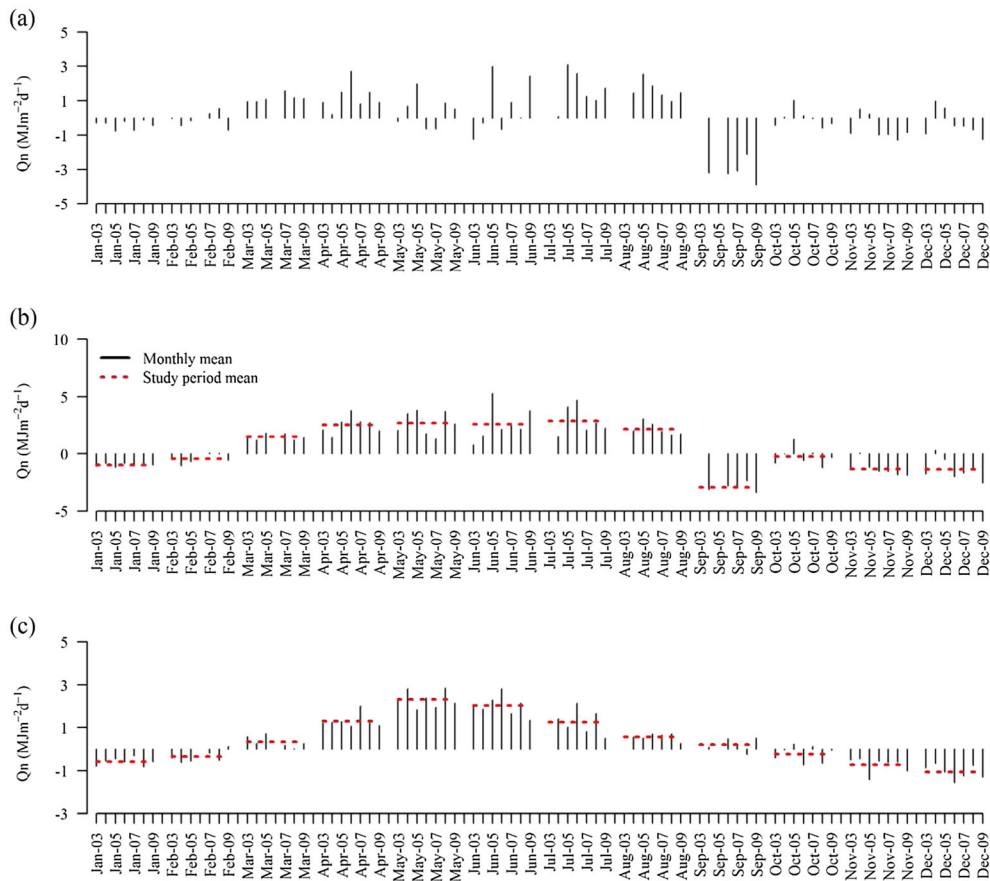


Figure 7. Monthly average net energy total: (a) moorland minus forest difference, (b) moorland, and (c) forest

driving inter-annual variability in net energy exchange. Between March and September, net radiation was the predominant energy source, and latent heat was the predominant sink in both the moorland and forest reaches. Sensible heat and bed heat were minor components of the energy budget in both reaches (Figure 8). Net radiation and latent heat exhibited greater inter-annual variability in the moorland reach (Table III). When net energy gain in the moorland reach was less than the forest, this was typically caused by two atypical scenarios: (1) net radiation receipt in the moorland was lower than the long-term mean (during May 2003 and 2006 and June 2006; Figure 9) or (2) latent heat loss in the moorland was greater than long-term means (during May 2007 and June 2003 and 2004; Figure 10). Net radiation and latent heat flux in the forest reach during these months was closer to long-term means (Figures 9 and 10, respectively).

Energy sources and sinks shifted markedly between autumn and winter months. During September, net radiation was the predominant heat source and latent heat the predominant heat sink. However, in October, net radiation became a heat sink, and sensible heat became a major heat source in both reaches, as did bed

heat flux in the moorland. Latent heat was the predominant sink in both reaches during October and a minor sink between November and February (Figure 8). Sensible heat, latent heat and net radiation were more variable between years in the moorland reach (Table III). Occasions when the moorland reach received more energy than the forested reach were associated with two atypical energy exchange conditions in the moorland: (1) net radiation gains occurred (during October 2004 and December 2005; Figure 9) and (2) high sensible heat gains occurred (during February 2007 and 2008, October 2005, November 2004 and December 2004; Figure 10). During these months, net radiation and sensible heat fluxes in the forest were typically closer to long-term means and more variable about long-term means in the moorland (Figures 9 and 10, respectively). However, in contrast to the spring and summer months, atypical energy exchange conditions also occurred in the forest on two occasions, causing the reach to lose more energy than the moorland: (1) during December 2005, the forest received extremely low sensible heat gain, and (2) during October 2006, latent heat loss was unusually high for the forest (Figure 10).

INTER-ANNUAL VARIABILITY OF THE FOREST EFFECT ON STREAM TEMPERATURE

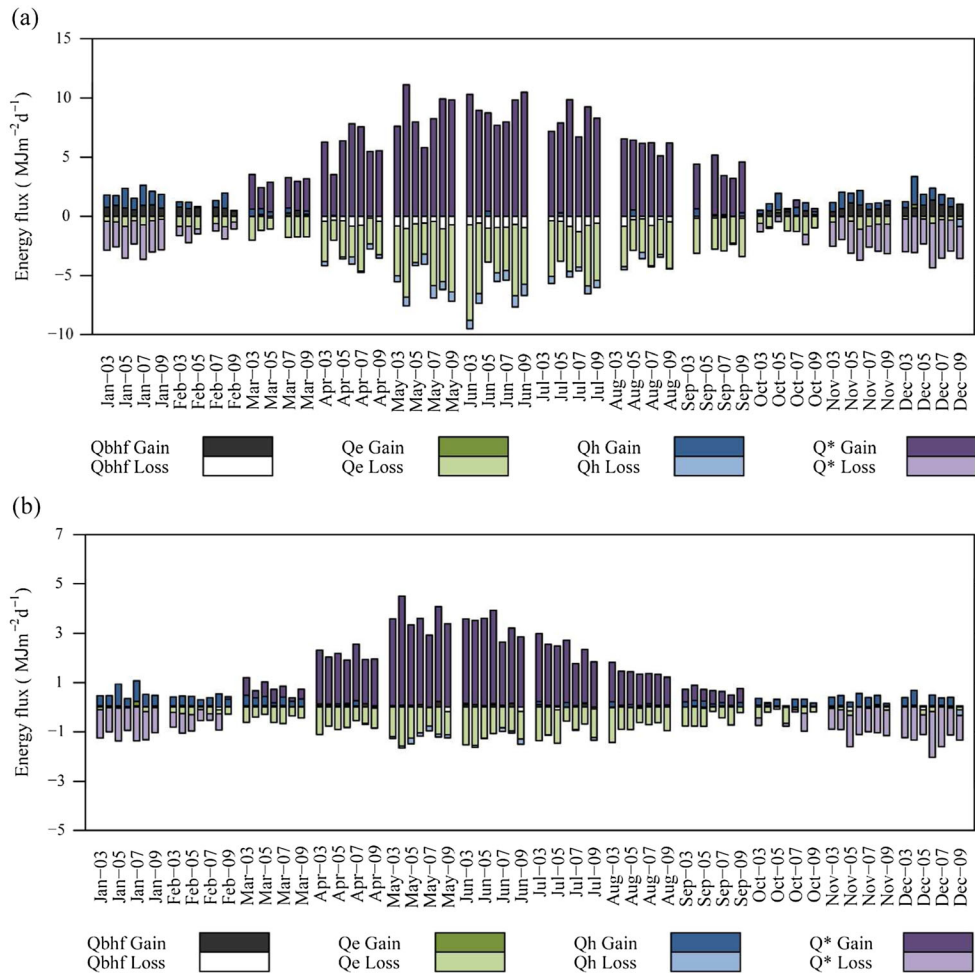


Figure 8. Monthly average daily total contributions of energy sources and sinks to energy gains and losses: (a) moorland and (b) forest

DISCUSSION

The 7-year dataset presented here provides improved understanding of the effects of semi-natural riparian forest on riparian micro-climate, energy exchange and stream temperature dynamics. Inter-annual variability in riparian micro-climate, energy exchange and stream temperature was typically greater in the moorland than the forest reach, especially during spring and summer. Marked inter-annual variability in moorland micro-climate and energy exchange variables (cf. more stable forest environment) drove considerable inter-annual variability in the magnitude of temperature differences observed between reaches.

Effects of contrasting riparian land use on inter-annual water temperature dynamics

Mean monthly water temperatures were up to 2.1 °C warmer in the moorland than the forest, and thus, the differences are comparable with those observed for conifer plantations and semi-natural forest in the UK

(Webb and Crisp (2006), Hannah *et al.* (2008), Brown *et al.* (2010) and Broadmeadow *et al.* (2011)). However, inter-comparisons between studies should be made with caution because the spatial configuration of the catchment in which a study is conducted may influence the magnitude of temperature differences observed (Gomi *et al.*, 2006). In the present study, the stream flowed through the moorland for ~2.5 km prior to flowing through ~1.5 km of forest. In pre-harvesting and post-harvesting approaches, the entire riparian corridor upstream of the monitoring site is forested. Thus, in the present study, the relatively short distance the water flowed through the forest was likely to be associated with longitudinal advection of heat into the forested reach from the moorland, which may have influenced the magnitude of observed differences in water temperature between sites.

During spring and summer months, water temperature in the moorland varied considerably between years, compared with the relatively stable forest reach (Johnson and Jones, 2000). Consequently, the presence of riparian

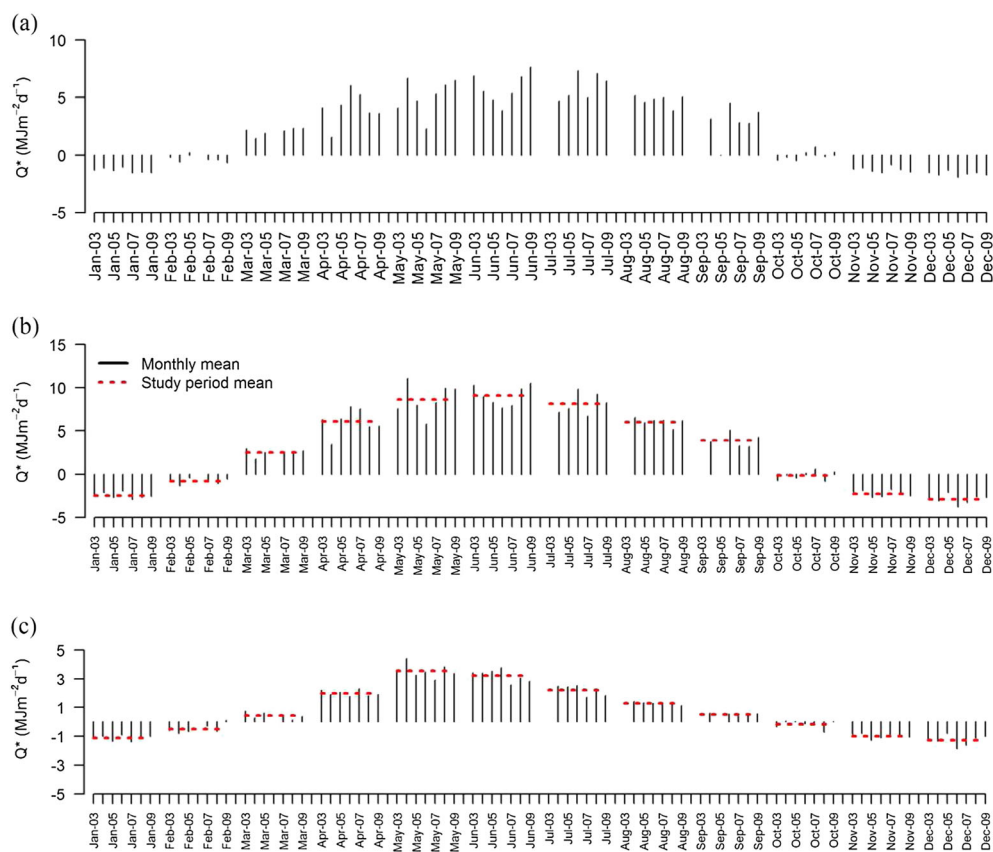


Figure 9. Monthly average net radiation total: (a) moorland minus forest difference, (b) moorland, and (c) forest

forest moderated inter-annual variability in water temperature and mitigated against the highest and lowest temperatures, which were observed only in the open, exposed moorland. The stream energy budgets calculated for the moorland and forest reaches during autumn and winter months suggest that water column temperatures should have been cooler and more variable between years in the moorland. However, autumn and winter water temperatures in the moorland were actually warmer and as stable in the moorland reach. This is attributed to reach-scale contributions of heat from groundwater that enters the channel due to a valley constriction immediately upstream of the moorland site (Malcolm *et al.*, 2005). These reach-scale contributions of groundwater are not thought to have been adequately characterised by the bed heat flux plate, which measured only point-scale heat exchanges between the streambed and water column. The temperature of long-residence well-mixed groundwater is generally stable and a few degrees above mean air temperature (Story *et al.*, 2003; O'Driscoll and DeWalle, 2006; Tague *et al.*, 2007; Herb and Stefan, 2011). For example, groundwater temperature in the upper levels of British aquifers is around 10–11.5 °C year-round (Bloomfield *et al.*, 2013) compared with 10.5–12.5 °C for mean annual air temperature (Garner *et al.*,

2013). Thus, groundwater discharge is thought to have provided inter-annual stability and warmer water temperatures in the moorland reach during the autumn and winter, an assertion partially supported by the available bed heat flux data and previous hydrological studies of the site (Malcolm *et al.*, 2004b). In contrast, bed heat flux in the forested reach was an extremely minor driver of net energy. Groundwater inflows have confounded previous studies of the influence of riparian forest water temperatures (e.g. Story *et al.*, 2003; Moore *et al.*, 2005b; Leach and Moore, 2011). However, this was only true for the autumn and winter temperatures in the present study where heat fluxes were generally small, and as such, bed heat flux could be proportionally large. Analysis of water temperatures was not confounded in spring and summer when energy exchange due to bed heat flux was estimated to be a very minor component of the energy budget in both reaches.

Drivers of inter-annual net energy exchange processes

In both the moorland and forest reaches, the stream energy budget was driven primarily by net radiation. This is consistent with previous studies (Brown, 1969; Sinokrot and Stefan, 1993; Webb and Zhang, 1997; 1999; Evans

INTER-ANNUAL VARIABILITY OF THE FOREST EFFECT ON STREAM TEMPERATURE

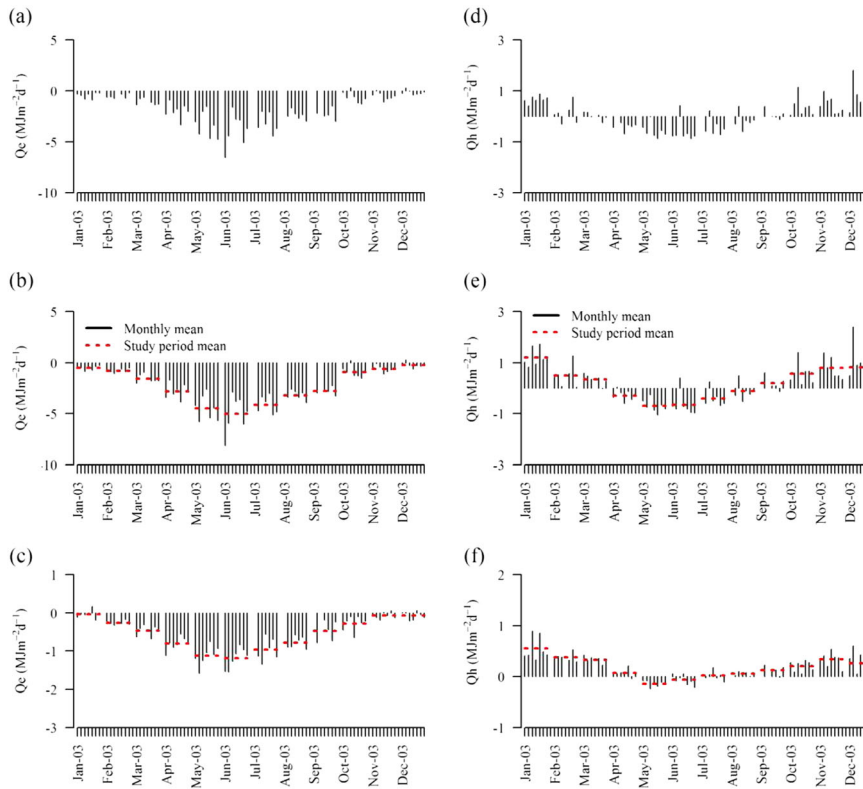


Figure 10. Monthly average daily total latent heat(a) moorland minus forest difference, (b) moorland, and (c) forest. Monthly average daily total sensible heat: (d) moorland minus forest difference, (e) moorland, and (f) forest

et al., 1998; Hannah *et al.*, 2004; Moore *et al.*, 2005b; Hannah *et al.*, 2008; Leach and Moore, 2010; MacDonald *et al.*, 2014; Leach and Moore, 2014). Latent heat was an important driver year-round, whereas sensible heat was important in autumn and winter months (Webb and Zhang, 1997; 1999; Hannah *et al.*, 2004; Hannah *et al.*, 2008). Bed heat flux was an important energy source in the moorland reach in autumn and winter (Effects of Contrasting Riparian Land Use on Inter-annual Water Temperature Dynamics).

The most extreme net energy gains and losses occurred in the moorland reach, whereas net energy exchanges in the forest were more stable between years. The moorland reach was not sheltered from variable meteorological conditions, which varied substantially between years, most notably as follows: (1) wind speed, which drove latent and sensible heat exchange (Hannah *et al.*, 2008), and (2) cloud cover conditions, which drove net radiative exchange (Johnson and Jones, 2000; Hannah *et al.*, 2004). In contrast, the forest canopy during spring and summer and (to a lesser extent) tree trunks and crowns in autumn and winter shaded and sheltered the forest reach (Malcolm *et al.*, 2004a) from prevailing wind and cloud cover conditions (Guenther *et al.*, 2012). Sheltering produced a more consistent micro-climate, which produced more consistent turbulent and radiative heat flux between years.

The moorland reach typically gained more energy than the forest reach in spring and summer and lost more energy in autumn and winter (Hannah *et al.*, 2008). However, when atypical, low net energy gain occurred in the moorland reach due to the following: (1) high latent heat loss as a consequence of high wind speed or (2) low net radiation due to overcast daytime skies or clear nights (Johnson and Jones, 2000); the forested reach could experience greater energy gain as a result of its greater relative stability. Similarly, when atypical low net energy loss occurred in the moorland during autumn and winter months due to high sensible heat gain due to low wind speed (Webb and Zhang, 1997; Hannah *et al.*, 2004; Hannah *et al.*, 2008) or low net radiation loss due to clear sky days or cloudy nights, the forest reach lost relatively more energy.

CONCLUSIONS

This study represents an important addition to the existing literature on the effects of riparian woodland on stream temperature. The data offers a unique long-term perspective on stream temperature, riparian micro-climate and energy exchanges in semi-natural forest and moorland (no trees) reaches that has not been seen previously.

The results provide new insights as to the potential of riparian vegetation to mitigate against stream water temperature extremes under present and future climates and, most importantly, the conditions under which smaller or larger forest effect sizes may be expected.

Water temperature, wind speed and energy exchange dynamics were typically more stable between years in the forest reach and more variable in the moorland (Hypothesis 1). Thus, the presence of riparian forest was associated with mitigating thermal and net energy flux variability. High inter-annual variability in the moorland reach caused considerable inter-annual variability in between-reach differences in water temperature, wind speed and net energy exchange (Hypothesis 2). Enhanced variability in the moorland reach was the consequence of riparian micro-climate being strongly coupled to variable prevailing meteorological conditions, especially wind and cloud cover (driving radiative and turbulent heat exchanges, respectively). In contrast, the presence of riparian vegetation in the forest provided shelter from variable wind and cloud cover conditions, and thus, the micro-climate and energy exchange processes were more stable between years (Hypothesis 3).

Planting of riparian vegetation is advocated as an effective way to mitigate stream water thermal extremes (Zwieniecki and Newton, 1999; Forestry Commission, 2011). Under present UK climate variability and in reaches where water column-streambed exchanges are minor, riparian forest downstream of open moorland provides an environment for freshwater species that is typically cooler than moorland in spring and summer, when thermal extremes occur. However, this is not the case when as follows: (1) net radiation gain is low in the moorland reach as a result of overcast skies during the day and/or clear skies at night; or (2) persistent strong winds enhance latent heat loss from moorland reaches; and consequently, water temperatures are low in both reaches. Consequently, the effectiveness of riparian planting could vary depending on future climatological conditions associated with environmental change.

Future climate change is anticipated to include increased long-wave radiation flux from the atmosphere (Wild *et al.*, 1997); the effect of this on the energy balance, and consequently water temperature, would be similar to conditions observed at present under overcast skies. Future climate is also anticipated to be characterised by reduced summer rainfall. In catchments such as the Gironck Burn, where groundwater residence times and active storage contributions to streamflow are low, summer discharges are expected to decline (Cappel *et al.*, 2013) with consequences for maximum temperatures. To quantify the effects of riparian forest under climate change would require reliable information on the likely magnitude and variability of climate and hydrological processes in the future.

Hydrological models coupled with process-based stream temperature models (e.g. Caissie *et al.*, 2007; Moore *et al.*, 2005b; Leach and Moore, 2011) driven by downscaled probabilistic climate change projections offer considerable potential for such research.

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