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A comparison of stream water temperature regimes from open and afforested moorland, Yorkshire Dales, northern England

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Abstract

Despite the known importance of water temperature for river ecosystems, the thermal regime of streams and rivers can be heavily modified by afforestation. Although the nature of the heat budget affecting streams in forested catchments shows high variability in space and time, most studies of stream temperature response to afforestation have lacked replication among streams. This study examined the impacts of coniferous forest plantations on stream water temperature at six sites (three forested and three open moorland) in the Yorkshire Dales, northern England. Our aim was to test the hypothesis that afforestation would alter the thermal regime of streams, leading to reduced year-round thermal variability, and cooler summer/warmer winter water temperatures, relative to streams flowing across open moorland. Data collected from April 2007 to March 2009 showed similar thermal dynamics among all six streams over the study period, although variability in forested streams was markedly lower as expected. Mean and maximum daily water temperature were significantly higher in open moorland streams for much of the year but while some forested streams were warmer than individual moorland streams during winter months (November to February), there was considerable overlap in water temperature between moorland and forest streams. Most stream temperature records showed evidence of low/no winter flow and freezing. These results contrast with many previous studies which have reported warmer temperatures in forested versus open moorland streams during winter, a finding which most likely reflects site-specific hydrological, geomorphological and climatological influences on water temperature in addition to afforestation. This study demonstrates the need for replication of hydrological monitoring when examining the effects of basin-scale management practices and provides further evidence for changes in stream thermal regime following afforestation, a practice which is likely to increase in future due to growing demands for increased forest cover in the UK uplands.

INTRODUCTION

The components that make up the energy budget of rivers and streams are complex and vary both temporally and spatially (Webb and Zhang, 1999; Hannah et al., 2004; Caissie, 2006). Energy inputs to streams may occur through incident short-wave (solar) and long-wave (downward atmospheric) radiation, condensation, friction at the channel beds and banks, and chemical and biological processes. Losses may include reflection of solar radiation, emission of long-wave (back) radiation and evaporation. Sensible heat and water column-bed energy transfers may cause gains or losses. In addition to these exchanges, energy may be advected by in/out flowing stream discharge, evaporated water, groundwater up/downwelling, tributary inflows and precipitation. Improvements in understanding the natural dynamics of, and human influences on, these processes are increasingly being made due to a recent upturn in the availability of accurate and reliable temperature datalogging technology (Webb et al., 2008).

Water temperature is widely recognised as one of the most important water quality parameters. For example, it plays a major role influencing the biological composition of streams and rivers and functional processes such as organic matter decomposition and nutrient cycling (Vannote and Sweeney, 1980; Weatherley and Ormerod, 1990a; Poole and Berman, 2001; Acuňa et al., 2008). Water temperature influences the chemical characteristics of running waters by affecting the solubility of oxygen and trace metals, and influencing pH (Berner and Berner, 1996). Despite the known importance of water temperature for river ecosystems, the thermal regimes of many streams and rivers have been modified by humans through direct point sources of thermal pollution (e.g. power stations and industry), river regulation, and afforestation/deforestation (Webb et al., 2008).

The presence of a forest canopy has long been known to modify the amount of solar radiation and other meteorological factors influencing stream temperatures (Pluhowski, 1972; Moore et al., 2005a) but the nature of the heat budget affecting streams in forested catchments typically shows high variability in space and time. Compared to open environments, forests provide a microclimate of lower wind speeds, higher humidity and less variable air temperature (Hannah et al., 2008). Dense canopies can reduce solar radiation by as much as 90%, effectively isolating streams from their main source of energy (i.e. incoming shortwave radiation: Sinokrot and Stefan, 1993; Poole and Berman, 2001). In North America, the effects of forest harvesting on stream temperature have been of concern for 50+ years due to the potential for increased water temperature to negatively affect fish populations (e.g. Johnson and Jones, 2000; Moore et al., 2005b). Several studies were undertaken in the 1990s in north Wales which generally showed lower stream water temperatures under coniferous plantations (Weatherley and Ormerod, 1990b; Webb and Crisp, 2006). However, the effect of afforestation on stream water temperature has received only minimal attention in other parts of the UK, with most studies being from Scotland (Malcolm et al., 2004; Webb and Crisp, 2006; Hannah et al., 2008).

Some recent studies have provided insights into the likely effects of upland afforestation on water temperature. Mean stream water temperatures were found to be reduced by ~0.4 to 0.5°C in coniferous forests in north Wales and southwest Scotland, respectively (Crisp, 1997; Webb and Crisp, 2006) while mixed forestry in the Cairngorms, Scotland was found to moderate temperature extremes (Malcolm et al., 2004). A study by Hannah et al. (2008) in mixed temperate forests in northeast Scotland suggested cooler, less variable water temperatures in forested reaches due to reduced net radiation but higher sensible and latent heat fluxes. However, all of these studies reviewed above examined the thermal regime of only one forested stream or one open canopy stream despite the known high spatial variability of energy budgets in forests. Only Weatherley & Ormerod (1990b) have considered the thermal regimes of replicate UK streams under afforested conditions, showing mean daily temperatures to be consistently lower in three forested streams compared to three grazed moorlands during spring and summer. The lack of replicated studies into forest effects on stream temperature means that questions remain about the transferability of findings related to stream temperature responses to afforestation.

In the UK there has been a substantial increase in upland tree cover over the past 50 years through coniferous plantations. Upland tree cover will also increase in the next 30 years as economic drivers may incentivise more coniferous plantation, and Scottish and English agencies aim to meet new targets for mixed broadleaf tree cover in the uplands (Natural England, 2009). Forests currently cover some 2.8M ha of the UK (~12% of the UK land surface) with approximately 58% of this cover being coniferous plantation. Much of the upland coniferous afforestation has occurred in areas where organic and organo-mineral soils dominate. Of particular concern is afforestation on blanket peats which cover approximately 15 % of the British Isles (Tallis, 1998). Blanket peatlands strongly influence stream hydrology, tending to encourage flashy regimes due to limited buffering of rainfall on near-saturated slopes (Holden and Burt, 2003b). Coniferous afforestation leads to alterations in upland blanket peatland hydrological processes with associated water quality changes, in particular acidification (Reynolds et al., 1988; Neal et al., 1992a; Reynolds et al., 1992). Despite the concerns about afforestation damage to peatland environments, the decreasing profitability of open moorland, concerns about the need to reduce downstream flood risk and a desire to mitigate climate change may lead to upland landowners turning over more of their land to plantations in the near future (Holden et al., 2007; Natural England, 2009).

This study examined the impacts of coniferous afforestation on the thermal regime of six streams in the Yorkshire Dales, northern England, where there has been recent conversion of open blanket peat moorland to coniferous plantation. No studies of afforestation effects on stream thermal regimes have been undertaken in this region. Water temperature measurements were made for replicate open moorland and afforested study basins, so that spatial variability in the effects of afforestation could be examined. We hypothesised that coniferous forest plantations would alter the thermal regime of blanket peatland streams, leading to reduced year-round thermal variability with cooler summer and warmer winter temperatures relative to open moorland streams. The study ran for two annual cycles and involved high resolution (15 min) water temperature and meteorological measurements enabling accurate characterisation of diurnal dynamics and thermal extremes.

METHODS

Study area

Field observations were made in the Green Field Beck and Oughtershaw Beck river basins, Upper Wharfedale (Figure 1), east of Pen-y-Gent in the Yorkshire Dales National Park, northern England (54º2'N; 2°2'W) between 1 April 2007 (day 91) and 31 March 2009 (day 90). Hereafter, dates are referred to using the calendar day of the year and time is quoted as Greenwich Mean Time (GMT). The Oughtershaw basin is predominantly open blanket peat moorland (Wallage et al., 2006) whereas the Green Field basin is predominantly covered by Spruce forest (Lane et al., 2008). The Oughtershaw basin lies directly to the north of the Green Field basin and therefore the two share similar physical characteristics and drain from west to east. Both basins lie on Carboniferous-age Great Scar Limestone, Yoredale Series and Millstone Grit overlain with a thin layer of glacial boulder clay which provides an impermeable substrate over which blanket peat has developed. Oughtershaw is dominated by *Eriophorum* species with some *Sphagnum* species present. The Green Field basin covers an area of 12.4 km^2 and Oughtershaw 13.8 km^2. Altitude ranges from 364 m to 602 m above sea level in the Green Field basin, and from 364 m to 668 m above sea level in the Oughtershaw basin. At the village of Beckermonds, the two streams converge forming the headwaters of the River Wharfe. The annual average precipitation, 1981-2008 inclusive, was 1817 mm ranging from 1383 mm in 1996 to 2457 mm in 2008.

Afforestation of the Green Field basin first occurred between 1970 and 1975 by Green Field Forestry Trust (*G. Hay, United Paper Mills [UPM] TilHill, personal communication*) and trees currently cover an area of 10.9 km^2. Sitka spruce (*Picea sitchensis*) is the dominant tree species covering over 64% of the plantation, with the remainder being Norwegian Spruce (*Picea abies*), and a few mixed broadleaf species. The forest is currently managed by UPM TilHill with areas intended to be felled and restocked on a 25 year rotation. However, adequate road access for logging vehicles has yet to be installed and the commencement of deforestation remains uncertain.

Field methods

Three tributaries were chosen for detailed study in both study basins (Table I). All were second order streams, approximately 2-3 m wide and study locations were established approximately 50 m upstream from the confluence with the main beck. Site M1 was an exception as the study site was established 50 m upstream of a small road which crosses the stream approximately 200 m upstream from Oughtershaw Beck. At each site, water column temperature was monitored using a Gemini Tinytag temperature datalogger housed in a radiation shield. Water temperature was recorded every 15 minutes, and dataloggers downloaded at quarterly intervals and internal clocks synchronised. All sub-zero water temperature records were removed from the time-series because rivers do not typically reach temperatures below 0°C unless super cooled (Mohseni and Stefan, 1999) and therefore all such records most likely indicated exposure of the sensor due to low/no flow. All dataloggers were cross-calibrated prior to field deployment to ensure comparable output data within the certified logger error of ±0.2°C.

Air temperature was monitored in the two study basins using a Gemini Tinytag temperature datalogger recording at 15 minute intervals from day 313 (November 9th), 2007. Prior to this date, air temperature was monitored adjacent to the two river gauges. However, the two dataloggers were damaged during overbank floods and all data were lost. Subsequently, we obtained a complete meteorological data set (30 min resolution) for April 2007 to March 2009 from a Davis weather monitor II automatic weather station located at 240m altitude ~20km northeast (54°22'25"N, 2°2'24"W), and established two new air temperature monitoring sites (Figure 1). Daily precipitation totals were obtained from the British Atmospheric Data Centre for the gauge at Beckermonds. To provide contextual information on periods of peak runoff, river stage data were obtained from the Environment Agency from rated cross-sections located in bedrock channels for the Oughtershaw Beck and Green Field Beck gauges. Discharge measurements were made for a range of stages using an electromagnetic current meter and stage-discharge rating curves were constructed. Flow records for Oughtershaw Beck were available only to calendar day 2, 2009 following flood damage to the stage recorder. The stage-discharge curve is uncertain for flows greater than 8 $m^3 s^{-1}$ at Green Field Beck but these high flow events occurred for <1% of the time.

Data analysis

Due to flashy stream flow conditions, temperature records for Sites F2 and F3 were interrupted by loggers being displaced onto the bank and then recording air temperature instead of stream water temperature. These erroneous data (which amounted to only 4.8% of the total number of recordings), and those recorded concurrently at all other sites, were therefore omitted from subsequent statistical analyses to ensure data sets of the same length. For all remaining data, Pearson's correlation coefficients were calculated as a measure of association between air-water temperatures, using 15 minute interval data from day 313, 2007 to day 90, 2009. Cross-correlation functions were computed to assess lags and leads in the maximum correlation between air and water temperature up to ±24 h. Mean water and air temperature statistics were calculated from 15 minute values rather than daily maxima and minima methods employed elsewhere (Holden, 2007). T-tests were used to compare monthly mean temperatures of the three open moorland and three forested streams. All statistical tests were undertaken with SPSS 15.0 and results were considered significant for $P<0.05$. Temperature-duration curves were constructed for 15 min water column temperatures at all sites. The form of these curves depicts the nature of thermal characteristics, as steeper gradient curves reflect higher variability (Brown et al., 2005; Brown et al., 2006).

To provide a detailed insight into thermal differences between forest and moorland streams over diurnal timescales using high resolution (15 min) datasets, eight 24 hour time periods were selected as follows: (i) diurnal water and air temperature records were examined for the two summer (June 21, 2007/2008) and two winter (December 21, 2007/2008) equinoxes to consider seasonal 'extremes'; (ii) two days were examined to consider the warmest and coldest days across the two-year record based on the highest and lowest mean daily air temperatures, and; (iii) the day in winter months (DJF) and the day in summer months (JJA) with the highest daily rainfall total were examined to consider responses to high magnitude precipitation events.

RESULTS

Precipitation events were frequent throughout the monitoring period (Figure 2a), although the highest magnitude event (56 mm) was observed in December 2007. The year 2008 was the wettest since monitoring began at Beckermonds in 1981. Mean daily air temperature at Swaledale followed an approximate sinusoidal pattern, peaking on July 27, 2008 (Figure 2; 20.4°C). However, peak instantaneous air temperature reached >25°C during both summer 2007 and 2008 at Swaledale, and >28°C at Oughtershaw on July 25, 2008 (Table II). Comparison of the shorter air temperature time-series recorded at Oughtershaw and Green Field (November 2007 to March 2008) revealed that Swaledale air temperature was on average warmer and had a smaller range than at Oughtershaw Beck and Green Field Beck (Table II). However, Swaledale records were significantly and strongly correlated with both Oughtershaw (R=0.98) and Green Field (R=0.99) indicating highly similar air temperature patterns over time. Both Oughtershaw Beck and Green Field Beck had similar flow regimes, with low baseflow and flashy responses to precipitation events (Figure 3), characteristics which were observed while in the field at the six tributaries used for water temperature monitoring. Despite similar catchment size and relief, runoff from Green Field Beck was typically higher than Oughtershaw Beck during storms.

Water column temperatures followed approximate sinusoidal patterns similar to the air temperature records (Figure 4). On average, water column temperatures for the forested sites in Green Field were cooler, less variable and with lower maxima than the moorland streams draining the Oughtershaw Beck basin (Table III). All six water column temperature monitoring sites had highly significant ($P<0.001$) correlations with local air temperature, although coefficients for the forested streams were all higher than those for the moorland streams (Table IV). Water temperature lagged air temperature by between 0.75 and 2.5 hrs, although there were no marked differences in lags between forested and moorland streams.

The pronounced annual temperature cycles at all forest and open moorland stream sites were further evident from monthly mean, maximum and minimum water temperatures (Figure 5). Open moorland streams had significantly higher mean temperatures for 12 of the 24 months studied but no significant differences were found from November 2007 to February 2008, or from July 2008 to February 2009. Maximum temperatures were significantly higher in moorland streams during late spring and summer months of each annual cycle (April – September) whereas there were no significant differences in monthly temperature minima. The difference in water column temperature maxima between forested and open moorland streams was further evident from temperature duration curves (Figure 6). Compared with the forested streams of the Green Field basin, the moorland streams in the Oughtershaw basin had steeper curves with higher temperature maxima. Minimum water temperatures were similar across all streams.

All three moorland sites showed highly similar temporal water column temperature patterns, particularly during warm time periods (e.g. day 209, 2008; Figure 4). Temporal patterns were similar to open moorland streams at the forested sites although somewhat muted (e.g. the warm water temperatures of day 170, 2007, and the low water column temperatures of day 355, 2007). Clear differences in diurnal temperature cycles were observed as a function of both season and forest cover (Figure 7). On June 21, 2007, average water temperature was up to 2.3°C higher (Table V), with markedly higher temperature maxima in moorland streams but similar minima across all sites (Figure 7a). On December 21, 2007, air temperature remained below freezing for the entire day, although temperature range at Green Field Beck was markedly lower than at

Oughtershaw Beck (Figure 7b). Two of the moorland streams (M1 and M3) had sub-zero temperatures for the entire day implying exposure of the sensor due to low/no streamflow, while temperatures at M2 and the three forested streams remained approximately constant throughout the day. June 21, 2008 had lower average, maximum and minimum air temperature than the preceding year's summer equinox, with an exceptionally large air temperature range for summer due to overnight sub-zero temperatures (Table V; Figure 7c). Water temperature maxima were high for moorland sites similar to June 21, 2007, although the magnitude of difference between moorland and forest streams was lower in 2008. December 21, 2008 was relatively warm for winter with higher air and water temperatures at all sites compared with December 21, 2007 (Figure 7d), and 7 mm of precipitation was recorded. Air temperature was marginally higher at Green Field Beck but average, maximum and minimum water temperatures were similar across all streams with only minimal variation during the day (Table V).

The warmest mean daily air temperatures at Oughtershaw and Green Field Beck were recorded on July 25, 2008 (17.6 and 17.3ºC, respectively; Table V). The diurnal air temperature cycle was strongly mirrored in the open moorland streams whereas thermal dynamics were relatively muted in the forest streams (Figure 8a). The coldest mean daily air temperatures were recorded on December 31, 2008. Air temperatures were sub-zero for the entire day, although a strong diurnal cycle was evident with temperatures at Oughtershaw Beck ranging from -13.0 to -0.9°C (Table V). However, water temperature records for two of the six streams (M1, F2) indicated exposure of the sensor due to low or no flow, whilst three streams (M2, M3, F3) had near freezing temperatures for the entire day (Figure 8b). Only stream F1 had water temperature above freezing with an average water temperature of 1.0°C and a minimum of 0.7°C (Table V).

On December 29, 2007, a total of 56mm of precipitation was recorded at Beckermonds and mean daily air temperatures were 2.7ºC (Green Field) and 3.0 ºC (Oughtershaw). Whilst the exact timing of the rainfall event at Beckermonds is unknown, 30 min records from Swaledale indicated two rainfall peaks, the first at 03:00GMT and the second at 14:00GMT. Air temperature records from Green Field and Oughtershaw dipped sharply at these times mirroring records from Swaledale but stream temperature records varied both among and within land use types, showing several increases and decreases throughout the day (Figure 8c). Temperature range was marginally higher for moorland than forested streams (Table V) but there was no clear distinction between the thermal regime streams of Oughtershaw or Green Field. The largest daily rainfall total recorded during summer months was 41.3mm on June 19, 2008, with 30 min records from Swaledale indicating a rainfall peak at 02:00GMT. Forest stream temperature varied less across the day than moorland streams (Figure 8d; Table V) but similar to the winter rainfall event there were clear overlaps in the thermal regimes of the six streams throughout the 24 hour period.

DISCUSSION

This study has demonstrated clear differences in the thermal regime of open and afforested moorland streams in the Yorkshire Dales, northern England. High resolution (15 min) sampling enabled the effects of forest plantations on water temperature diurnal cycles and extremes (maximum/minimum) to be explored in detail. Additionally, our study has provided insights into between-stream variability of thermal regime in forested catchments, whereas in many previous studies, only one stream has been used to characterise water temperature for either forest or open moorland (e.g. Greene, 1950; Neal et al., 1992b; Malcolm et al., 2004; Webb and Crisp, 2006). All open moorland streams typically had higher maximum water temperatures, despite similar climatological (air temperature, rainfall) and hydrological (river runoff) conditions to the forested study areas. In a manner similar to Malcolm et al. (2004), hydroclimatological datasets were used as a context for inferring the physical processes influencing thermal differences between the Oughtershaw Beck open moorland streams and the forested tributaries in Green Field.

Our observation that water temperature in streams lacking forestry ranged widely (average range for the three streams was 27.3°C), with higher temperature maxima compared to forested streams, is supported by findings from the River Twyi, Wales (Weatherley and Ormerod, 1990b), and Girnock Burn (Malcolm et al., 2004) and Loch Grannoch (Webb and Crisp, 2006) in Scotland. Similar results have been seen in studies from North America (Johnson, 2004; Moore et al., 2005b) and New Zealand (Rowe and Pearce, 1994) where forest streams have been compared to open canopy streams following deforestation. Open moorland streams in the UK flow through environments with only short riparian dwarf shrubs and grasses, meaning channels are typically openly exposed to the atmosphere. While air-water temperature relationships for tributary streams in the Oughtershaw Beck basin were marginally weaker than those at Green Field Beck, the open moorland streams were generally more responsive to temporal (diurnal to inter-annual) meteorological dynamics than forest streams. Incoming shortwave radiation, sensible heat flux and wind speed/humidity (thus latent heat fluxes) are major components of moorland stream energy budgets (Hannah et al., 2004; Hannah et al., 2008) and the relatively low thermal capacity of small streams such as those studied herein also contributes to the high magnitude of temperature fluctuations (Webb et al., 2003). Interestingly, there were no clear between-catchment differences in stream temperature response to high magnitude precipitation events in contrast to other studies that have shown changes of up to ±10°C (Chutter, 1970; Smith and Lavis, 1975; Brown and Hannah, 2007). This may be a reflection of the small stream size thus, minimal direct interception of precipitation. Additionally, the dominance of saturation-excess overland flow pathways in peatland systems (Holden and Burt, 2003b) means there are limited rainfall-induced contributions from other water sources during storms (e.g. deep groundwater) that could otherwise significantly alter the stream thermal regime. Furthermore, the timing of the rainfall events on the two days examined herein could account for the minimal stream temperature change (Brown and Hannah, 2007) because streams would be relatively cool during the night and perhaps less likely to show a large precipitation induced temperature response.

Malcolm et al. (2004) noted subtle differences in thermal regimes between five open moorland stream reaches as a consequence of reach-scale factors such as aspect and width:depth ratios. Results from Oughtershaw Beck supported these findings of between-stream thermal variability but did not fully support the hypothesised effect of aspect as average temperature in the north-facing site M2 was only 0.2°C lower (i.e. within datalogger error range) than the highest recorded mean moorland temperature at south-facing site M3. However, the south-facing site M3 did have the highest maximum temperature of any of the six sites which could be due to more direct receipt of incoming solar radiation. More replication of sites is required to properly elucidate the role of aspect and to consider the interactive role of other site-specific variables such as stream discharge dynamics and width:depth ratios.

Temperature records for sites M1 and M3 had the longest periods of interruption due to low/no flow during winter, whereas M2 flowed year-round. The very small hydraulic conductivity of blanket peats in all but the uppermost few centimetres of the peat mass (Holden and Burt, 2003a) means that these soils are poor regulators of baseflow. Often small peatland streams will dry up at any time of the year if there has not been rainfall, or if the upper layers of the peat remain frozen. Even though there is unfrozen water held in most of the peat in winter, the very low hydraulic conductivity at depth combined with a frozen upper layer means that water is held in situ and free drainage to the stream is inhibited. It may well be that freezing of the peat surface was more common on the exposed Oughtershaw Moss site than within the forested Green Field Beck catchment. Furthermore, forestry tends to increase the hydraulic conductivity of the peat through the action of tree roots, litter and forest drainage systems (Holden et al., 2004) and so very low flows might be better maintained (rather than no flow) in tributaries of Green Field Beck than in tributaries of Oughtershaw Beck.

In the forested tributaries of Green Field Beck, diurnal dynamics were typically dampened and water temperature was on average 0.8°C cooler than the moorland tributaries of Oughtershaw Beck. This difference was slightly greater than the 0.15°C recorded from the Cairngorms (Hannah et al., 2008), 0.4°C reported from North Wales by Crisp (1997), 0.5°C from southern Scotland by Webb & Crisp (2006) and 0.6°C for a tributary of the Upper River Severn, Wales (Stott and Marks, 2000). These differences are likely due to a combination of differences in climatic conditions during each of the aforementioned studies, as well as more general stream hydrogeomorphological characteristics (i.e. length, aspect, width:depth, discharge: Brown and Hannah, 2008). Forestry characteristics such as tree species and density (Brown, 1969) also vary between study locations, and they can contribute to thermal heterogeneity within individual streams (e.g. Moore et al., 2005b).

In our study, forest cover had a significant effect on maximum stream temperature, with reductions of up to ~7°C as observed in several other studies (Kirby et al., 1991; Neal et al., 1992b; Webb and Crisp, 2006). One of the key reasons for discrepancies between the maximum water temperature of open canopy and forested streams is that shading leads to a significant reduction in net radiation during summer (Hannah et al., 2008). As net radiation is typically the major component of river energy budgets, water temperature dynamics are consequently dampened. A similar magnitude of maximum stream water temperature change between forested and clearfelled areas has been observed in North American studies (Johnson and Jones, 2000; Moore et al., 2005b). Anlaysis of diurnal temperature cycles for the three forested streams herein showed that site F3 was typically warmer on average compared with F1 and F2, and had with higher maximum and minimum temperatures. F3 has several small treeless clearings upstream of the monitoring site which allow incoming radiaton to reach the stream and thus heat the water in a manner not dissimilar to situations seen following forest harvesting (Swift and Messer, 1971; Johnson and Jones, 2000; Moore et al., 2005b). Inter-site differences in thermal regimes could also potentially cause differences in hydrological flow paths and groundwater inputs between individual study basins (Moore et al., 2005a) but further hydrological research is necessary at the study sites to elucidate the importance of these factors.

While forest stream temperatures are typically cooler than those of moorland streams in summer due to shading effects, some previous studies have found forest stream temperatures to be higher than those of open moorland streams during winter (Smith, 1980; Webb and Crisp, 2006; Hannah et al., 2008). It has been suggested that during winter, the canopy (in coniferous plantations) acts to ‘insulate’ the stream by maintaining warmer air temperatures and reducing long-wave radiation losses (Webb and Zhang, 2004; Webb and Crisp, 2006). Our results partially support the suggestion of warmer mean temperatures in forest streams during some winter months (i.e. Figure 5a; December and January of both years), but our consideration of three streams showed that these minor differences were not statistically significant. If our study had focused on one site per land use as per previous studies (for example choosing F1 v M1), mean

January 2007 water temperature for example would have been reported as being 0.5°C higher in the forested site. In contrast, comparison of F2 v M2 would have shown the moorland site as being 0.3°C warmer at this time. While we acknowledge that three streams per land-use represents only a minimal level of replication providing low statistical power, these results nevertheless highlight the need for replication of future stream temperature monitoring studies to avoid potential erroneous conclusions that can arise from inter-site thermal differences under the same land-use.

Coniferous plantations are often seen as having negative effects on peatland soils, runoff, river water quality and terrestrial biodiversity (Charman, 2002) yet their moderating effect on stream temperature extremes may be considered advantageous to poikilothermic stream dwelling organisms such as salmonids and some invertebrates (Hawkins et al., 1997; Malcolm et al., 2004). Maximum water temperatures in these Wharfedale forested study streams reached only 17.2°C compared with temperatures of up to 23.8°C in open moorland streams. The afforested streams in this study therefore offered thermal conditions well below the upper temperature limit of 22°C for juvenile Atlantic Salmon growth, and less than the 19.5°C limit at which adult Brown Trout typically stop feeding (e.g. Crisp, 1993; Elliott and Hurley, 1997). Nevertheless, temperature minima in both forested and open moorland streams were close to or below lethal limits for all stages of salmonid life cycles (Armstrong et al., 2003) which probably contributes to the low abundance of salmonids found in these Upper Wharfedale streams (Tetley, 1998). In contrast to large maximum water temperature differences between forest and open moorland streams, overall mean water temperature only reached up to 1.2°C higher in the open canopy Oughtershaw Beck tributaries. Nevertheless, even these seemingly minor thermal differences may be large enough to induce significant change in UK upland stream ecosystems. For example, a +1°C change to some Welsh headwater streams due to climate warming is considered likely to reduce spring abundances of benthic macroinvertebrates, which are a key food source for fish and other predators, by as much as 21% (Durance and Ormerod, 2007).

Afforestation has been the main cause of net moorland habitat loss over the past century (Holden et al., 2007) with an estimated 9% of upland UK peatland changed (Cannell et al., 1993). As the majority of this land use change has involved the planting of commercial coniferous trees (Forestry Commission, 2007), our study provides an insight into some of the likely wider effects of this land management practice on stream thermal regimes. Growing demands for increased tree cover in the UK uplands (Gimingham, 2002; Natural England, 2009), albeit with more mixed plantations as well as coniferous crops, mean that it is likely that there will be increased planting in future. Efforts to model ecosystem responses to upland afforestation to inform decisions about the spatial extent of planting (Nisbet and Broadmeadow, 2003) should clearly consider the effects on stream thermal regimes as exemplified herein.

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Table I. Water temperature monitoring site characteristics

	Green Field Beck basin			Oughtershaw Beck basin		
Site	**F1**	**F2**	**F3**	**M1**	**M2**	**M3**
Stream name	-	-	Green Field Beck	Mireing Gill	Long Gill	Blea Gill
Co-ordinates	54.22°N 2.20°W	54.21°N 2.23°W	54.21°N 2.26°W	54.24°N 2.21°W	54.23°N 2.21°W	54.24°N 2.23°W
Elevation (m)	325	361	388	458	376	393
Basin Area (km^2)	0.25	0.16	0.43	0.36	0.39	0.98
Slope (m per km)	173	150	94	161	198	153
Aspect	N	N	NE	SW	N	S

Table II. Air temperature statistics for the entire study period

	Swaledale air	**Swaledale air[a]**	**F air[a]**	**M air[a]**	**F air[b]**	**M air[b]**
Mean	9.2	7.7	5.5	5.4	5.5	5.5
Max	25.7	25.7	22.6	28.3	22.6	28.3
Min	-6.8	-6.8	-11.4	-17.2	-11.5	-17.8
Range	32.5	32.5	34.0	45.5	34.1	46.1
St. Dev	5.4	5.3	5.1	5.8	5.1	5.8

[a] Statistics for calendar day 313, 2007 to calendar day 90, 2008 for direct comparison of Swaledale, Oughtershaw (M) and Green Field (F) records, based on 30min data

[b] Statistics for calendar day 313, 2007 to calendar day 90, 2009 based on 15min data

Table III. Descriptive statistics calculated from 15 min water column temperature data

Site	F1	F2	F3	M1	M2	M3
Mean	6.9	6.9	7.0	7.7	7.8	8.1
Max	17.2	16.9	17.1	23.0	22.9	23.8
Min	0.0	0.0	0.1	0.0	0.0	0.0
Range	17.2	16.9	17.0	23.0	22.9	23.8
St. Dev	3.2	3.4	3.8	4.0	4.4	4.5

Table IV. Air-water correlation coefficients (R), cross correlation coefficients (X-R) and lag times (hr) based on15 min water column and air temperature records [All correlations were significant at $P<0.001$]

Site	R	X-R	Lag (hr)
F1	0.912	0.922	1.0
F2	0.927	0.941	0.75
F3	0.906	0.929	2.5
M1	0.891	0.914	0.75
M2	0.875	0.900	1.5
M3	0.864	0.900	2.25

Table V. Descriptive statistics for water and air temperature records (based on 15 min data) for the eight selected diurnal records. [- denotes no data]

		F1	F2	F3	M1	M2	M3	F air	M air
June 21, 2007	Mean	10.4	10.5	11.6	11.0	12.1	12.7	-	-
	Maximum	11.0	11.8	12.9	14.8	16.3	16.2	-	-
	Minimum	9.8	9.9	10.5	9.1	9.7	10.5	-	-
	Range	1.2	1.9	2.4	5.7	6.6	5.7	-	-
	St. Dev.	0.4	0.5	0.8	1.6	2.0	1.7	-	-
Dec. 21, 2007	Mean	2.0	0.9	0.9	-	0.2	-	-2.8	-4.2
	Maximum	2.6	1.6	1.2	-	0.5	-	-0.7	-1.1
	Minimum	1.0	0.0	0.2	-	0.0	-	-6.8	-11.2
	Range	1.6	1.6	1.1	-	0.5	-	6.1	10.1
	St. Dev.	0.3	0.5	0.3	-	0.1	-	1.6	2.7
June 21, 2008	Mean	8.0	8.0	8.7	8.2	8.9	9.6	7.9	7.7
	Maximum	9.2	9.1	9.4	9.3	10.3	10.5	13.7	14.1
	Minimum	6.2	7.3	8.1	6.8	7.2	8.6	1.9	-2.3
	Range	3.0	1.8	1.4	2.4	3.2	1.9	11.8	16.5
	St. Dev.	0.9	0.5	0.3	0.8	1.0	0.6	2.9	4.3
Dec. 21, 2008	Mean	6.1	6.2	5.9	5.9	6.1	6.4	7.8	7.5
	Maximum	6.3	6.4	6.3	6.3	6.4	6.9	8.7	8.4
	Minimum	5.8	5.8	5.4	5.6	5.7	5.9	6.8	7.0
	Range	0.6	0.6	0.9	0.7	0.8	1.0	1.9	1.5
	St. Dev.	0.2	0.1	0.3	0.2	0.2	0.3	0.5	0.4
Jul. 25, 2008	Mean	11.6	12.7	13.8	15.1	16.6	16.6	17.3	17.6
	Maximum	12.3	13.8	15.6	19.0	21.2	20.8	22.6	25.6
	Minimum	10.9	11.5	12.3	11.6	12.4	13.0	12.3	8.4
	Range	1.4	2.3	3.4	7.4	8.7	7.8	10.4	17.3
	St. Dev.	0.5	0.8	1.2	2.6	3.0	2.8	3.6	5.0
Dec. 31, 2008	Mean	1.0	-	0.2	-	0.0	0.1	-6.5	-8.1
	Maximum	1.8	-	0.4	-	0.1	0.1	-4.0	-0.9
	Minimum	0.7	-	0.1	-	0.0	0.1	-8.6	-13.0
	Range	1.0	-	0.2	-	0.1	0.1	4.7	12.1
	St. Dev.	0.3	-	0.1	-	0.0	0.0	1.2	3.5
Dec. 29, 2007	Mean	5.0	4.5	4.5	4.2	4.6	4.5	3.0	2.7
	Maximum	5.8	5.5	5.7	5.6	5.9	5.8	4.3	4.3
	Minimum	4.5	3.9	4.1	3.6	4.1	3.7	0.5	0.1
	Range	1.3	1.7	1.6	2.0	1.8	2.1	3.8	4.2
	St. Dev.	0.3	0.3	0.4	0.5	0.5	0.5	0.9	1.1
Jun. 19, 2008	Mean	9.0	8.9	9.6	8.8	9.6	10.3	10.1	10.2
	Maximum	9.5	9.1	10.3	10.1	10.8	12.0	12.4	13.2
	Minimum	8.6	8.6	9.0	8.1	8.8	9.0	8.5	6.4
	Range	0.8	0.6	1.3	1.9	2.1	3.1	4.0	6.7
	St. Dev.	0.3	0.2	0.4	0.6	0.6	0.9	1.1	1.4

Figure captions

Figure 1. Map of the Oughtershaw Beck and Green Field Beck study basins showing locations of water column temperature, air temperature, river gauge and precipitation gauge

Figure 2. (a) Total daily rainfall measured at Beckermonds gauge at the confluence of Oughtershaw Beck and Green Field Beck, and; mean daily air temperatures based on 30 min data measured at (b) Swaledale, (c) Green Field Beck, and (d) Oughtershaw Beck

Figure 3. Mean daily discharge for Oughtershaw Beck and Green Field Beck.

Figure 4. Mean daily stream water temperatures at (a) F1, (b) F2, (c) F3, (d) M1, (e) M2, and (f) M3

Figure 5. Monthly (a) mean, (b) maximum and (c) minimum water temperatures for forest and moorland streams [error bars = 1 standard deviation of the mean and asterisks denote significant differences at $P<0.05$]

Figure 6. Water temperature duration curves for forest and moorland streams

Figure 7. Diurnal temperature records for equinoxes: (a) June 21, 2007; (b) December 21, 2007; (c) June 21, 2008, and; (d) December 21, 2008. Note different y-axis scales for June and December figures

Figure 8. Diurnal temperature records for (a) July 25, 2008 [highest mean daily air temperature]; (b) December 31, 2008 [lowest mean daily air temperature]; (c) December 29, 2007 [highest winter daily precipitation total = 56mm], and; (d) June 19, 2008 [highest summer daily precipitation total = 41.3mm]. Note different y-axis scales

Fig 1.

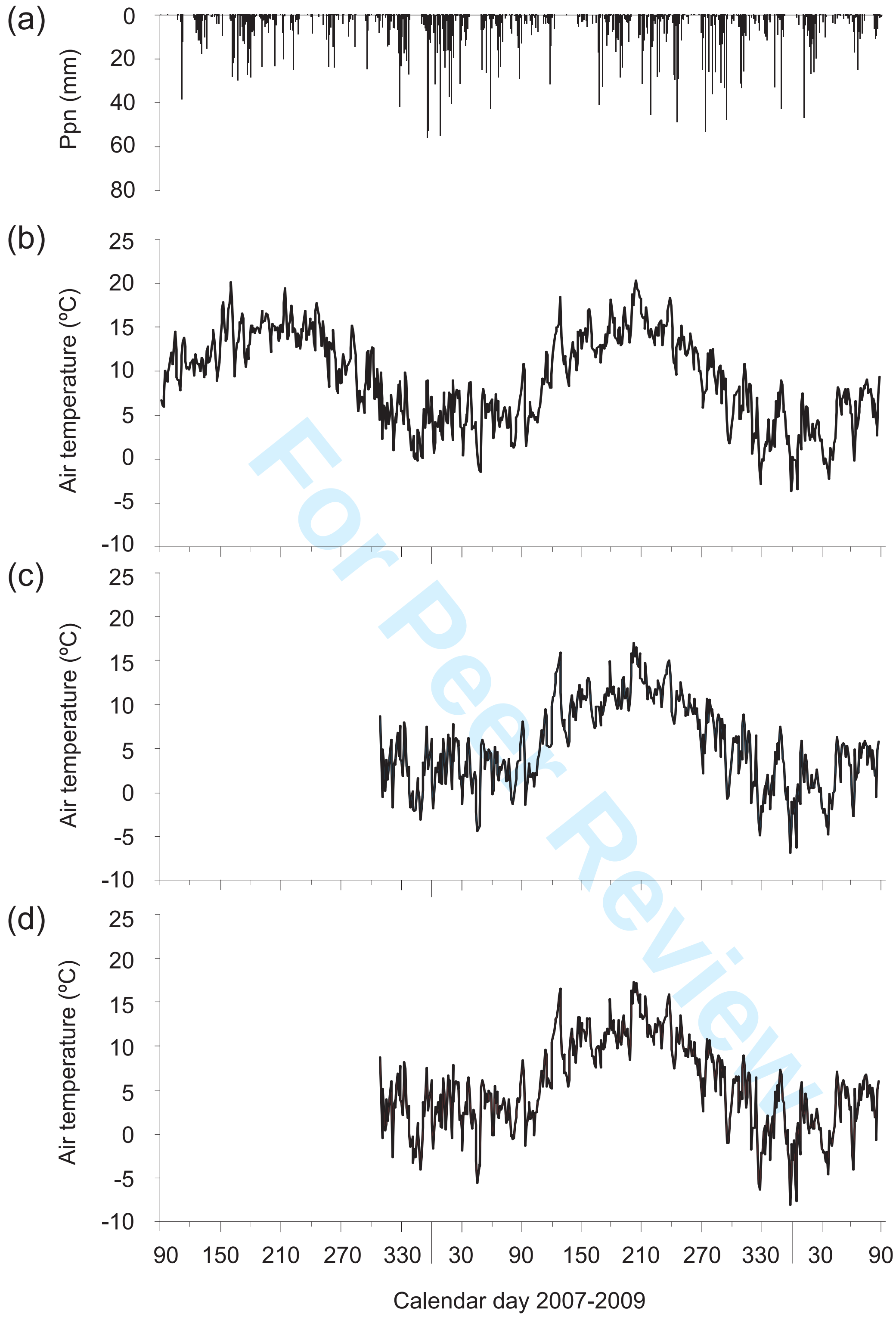

(a)
Ppn (mm)
0
20
40
60
80
(b)
Air temperature (ºC)
25
20
15
10
5
0
-5
-10
(c)
Air temperature (ºC)
(d)
Air temperature (ºC)
90
150
210
270
330
30
90
150
210
270
330
30
90
Calendar day 2007-2009

Fig. 2.

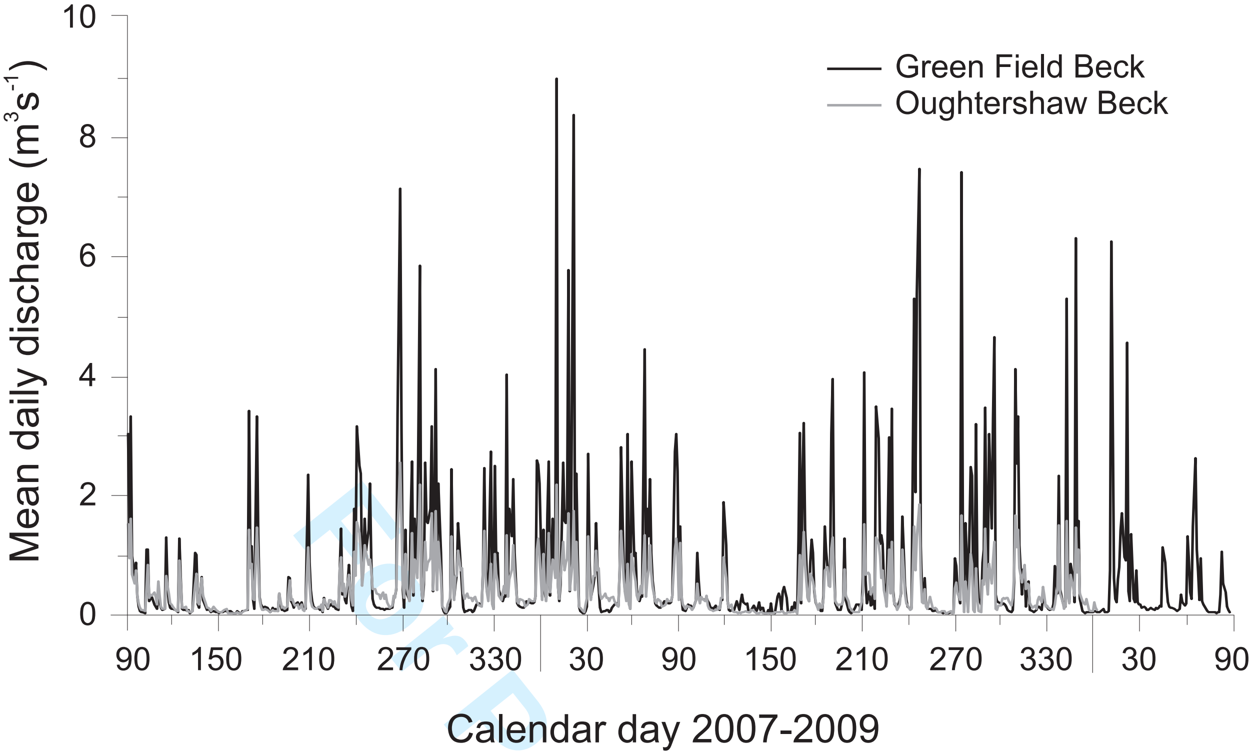
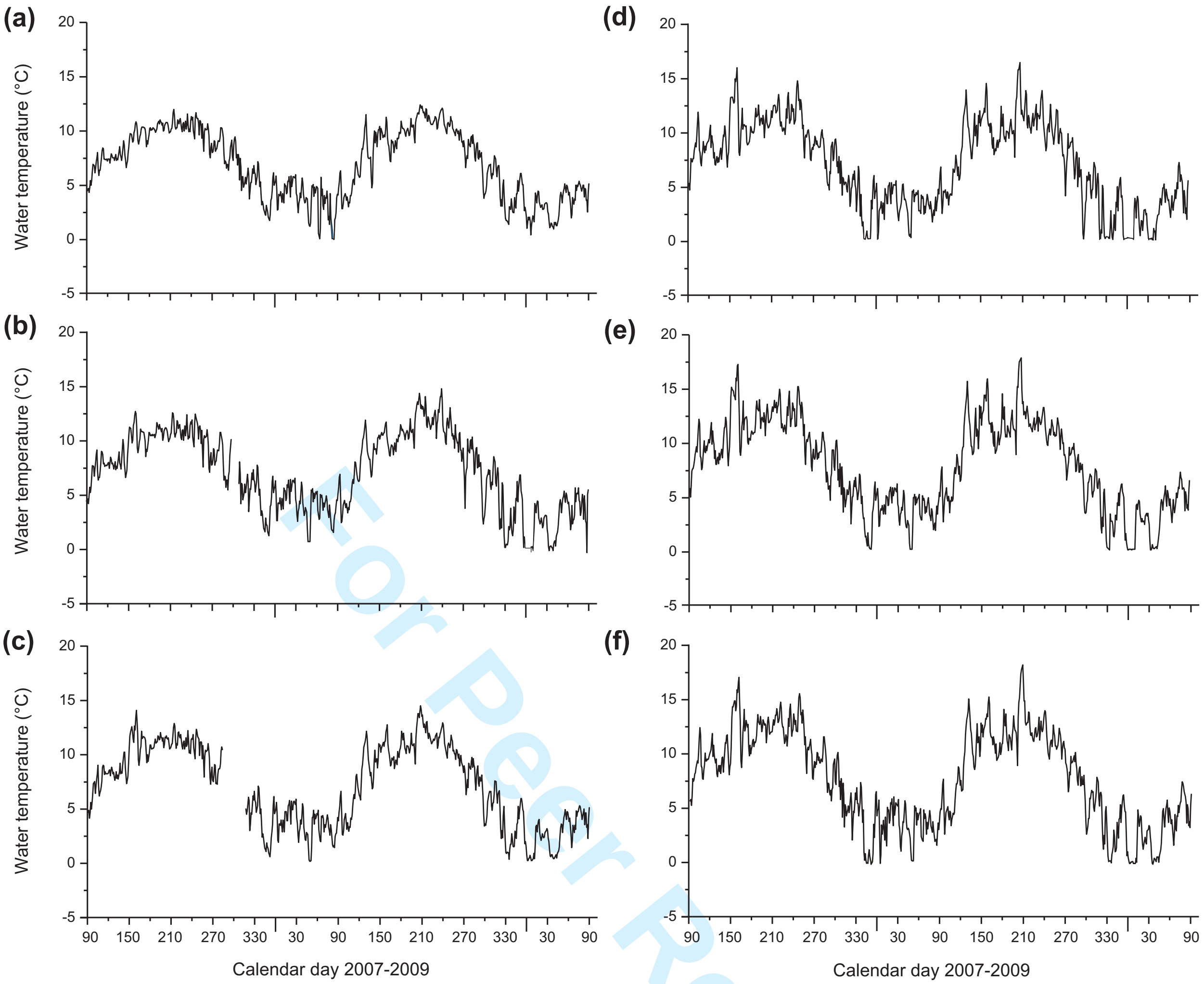

10
8
6
4
2
0
Mean daily discharge (m^3s^{-1})
Green Field Beck
Oughtershaw Beck
90
150
210
270
330
30
90
150
210
270
330
30
90
Calendar day 2007-2009

Fig. 3.

1


(a)
(b)
(c)
(d)
(e)
(f)
Water temperature (°C)
20
15
10
5
0
-5
90 150 210 270 330 30 90 150 210 270 330 30 90
Calendar day 2007-2009

2

3 **Fig. 4.**

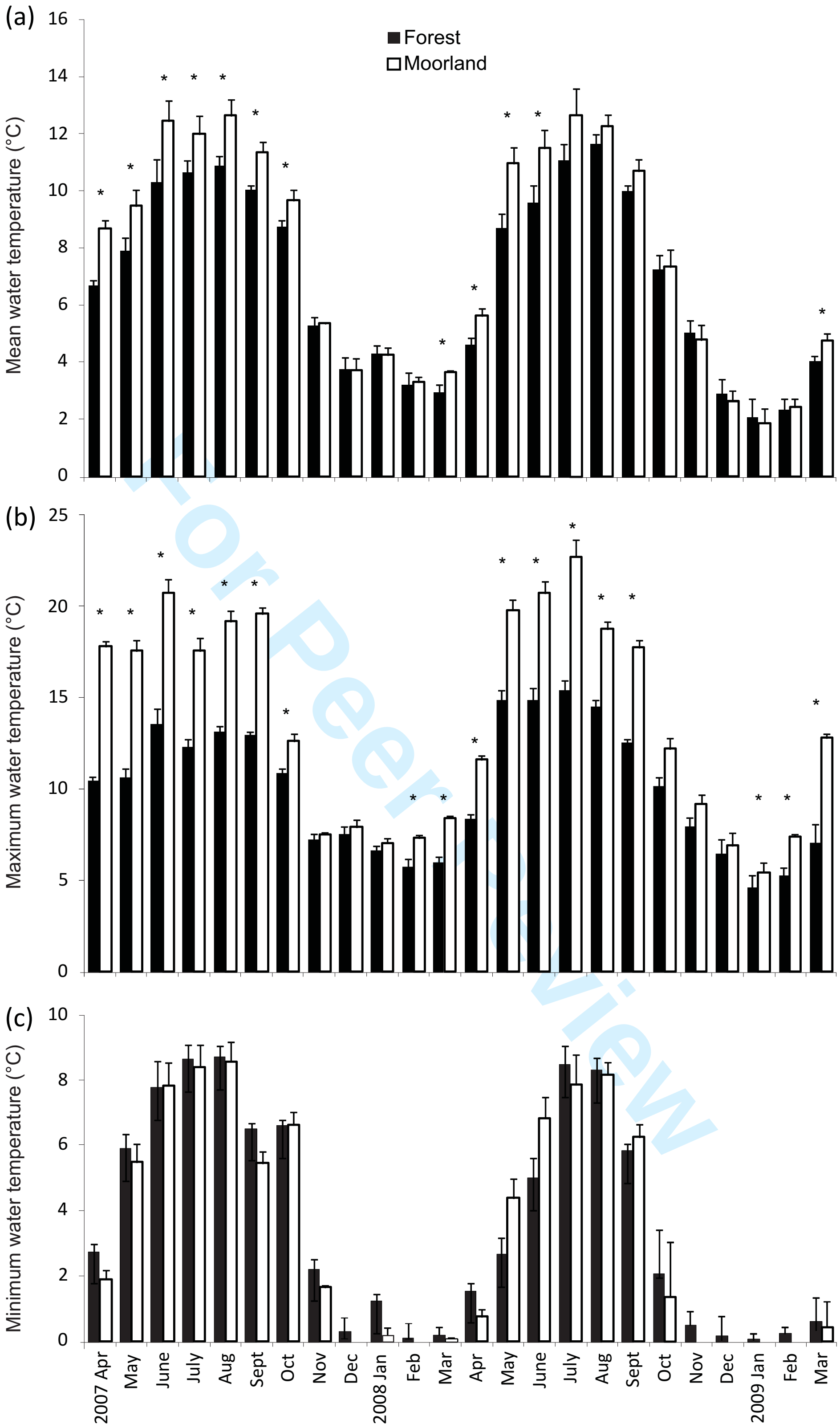
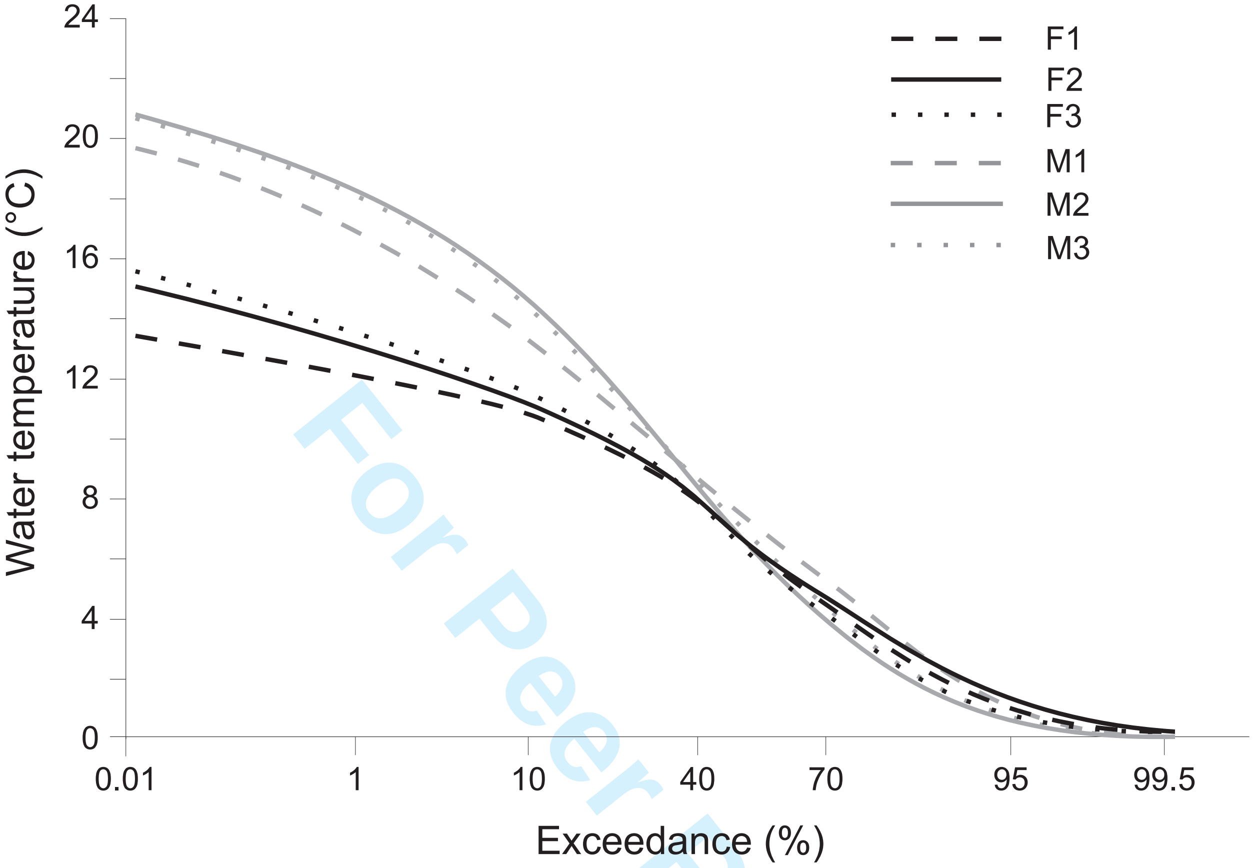

(a)
Forest
Moorland
Mean water temperature (°C)
0
2
4
6
8
10
12
14
16
(b)
Maximum water temperature (°C)
0
5
10
15
20
25
(c)
Minimum water temperature (°C)
0
2
4
6
8
10
*
2007 Apr
May
June
July
Aug
Sept
Oct
Nov
Dec
2008 Jan
Feb
Mar
Apr
May
June
July
Aug
Sept
Oct
Nov
Dec
2009 Jan
Feb
Mar

Fig. 5.

1


24
20
16
12
8
4
0
Water temperature (°C)
0.01
1
10
40
70
95
99.5
Exceedance (%)
F1
F2
F3
M1
M2
M3

2

3 **Fig. 6.**

4

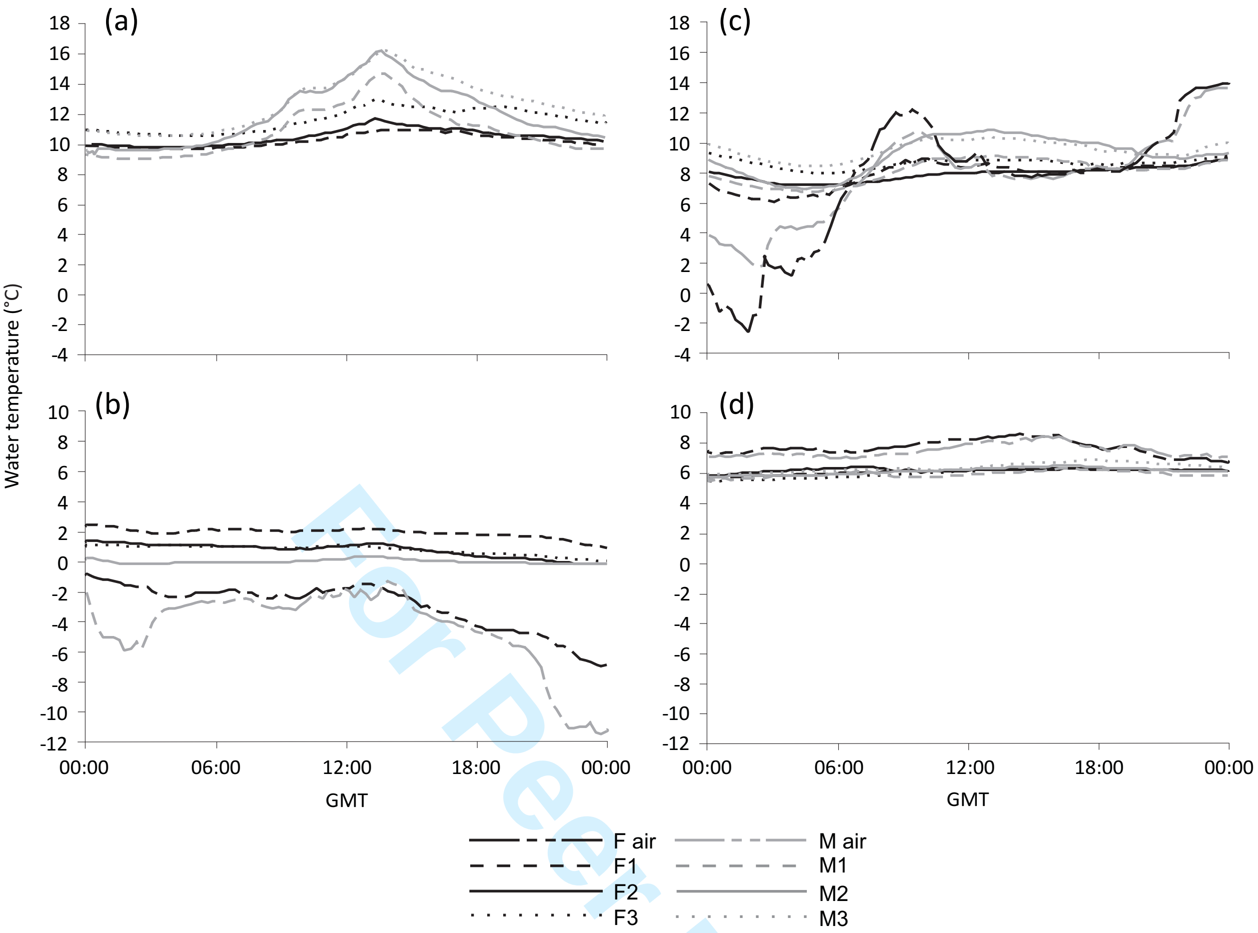

(a)
(b)
(c)
(d)
Water temperature (°C)
18
16
14
12
10
8
6
4
2
0
-2
-4
-6
-8
-10
-12
00:00
06:00
12:00
18:00
00:00
GMT
F air
F1
F2
F3
M air
M1
M2
M3

Fig. 7.

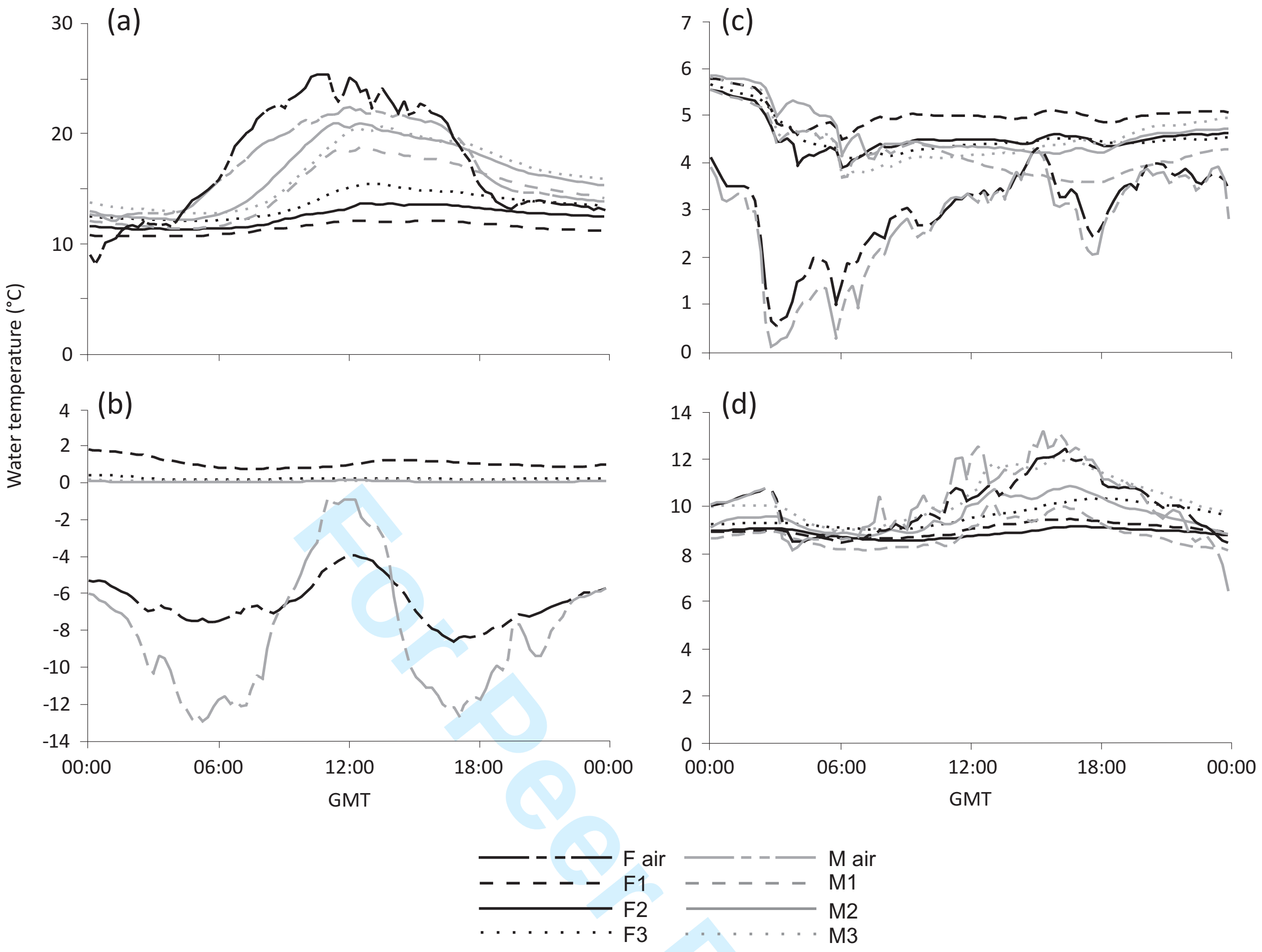

(a)
(b)
(c)
(d)
Water temperature (°C)
30
20
10
0
4
2
0
-2
-4
-6
-8
-10
-12
-14
7
6
5
4
3
2
1
0
14
12
10
8
6
4
2
0
00:00
06:00
12:00
18:00
00:00
GMT
F air
F1
F2
F3
M air
M1
M2
M3

Fig. 8.

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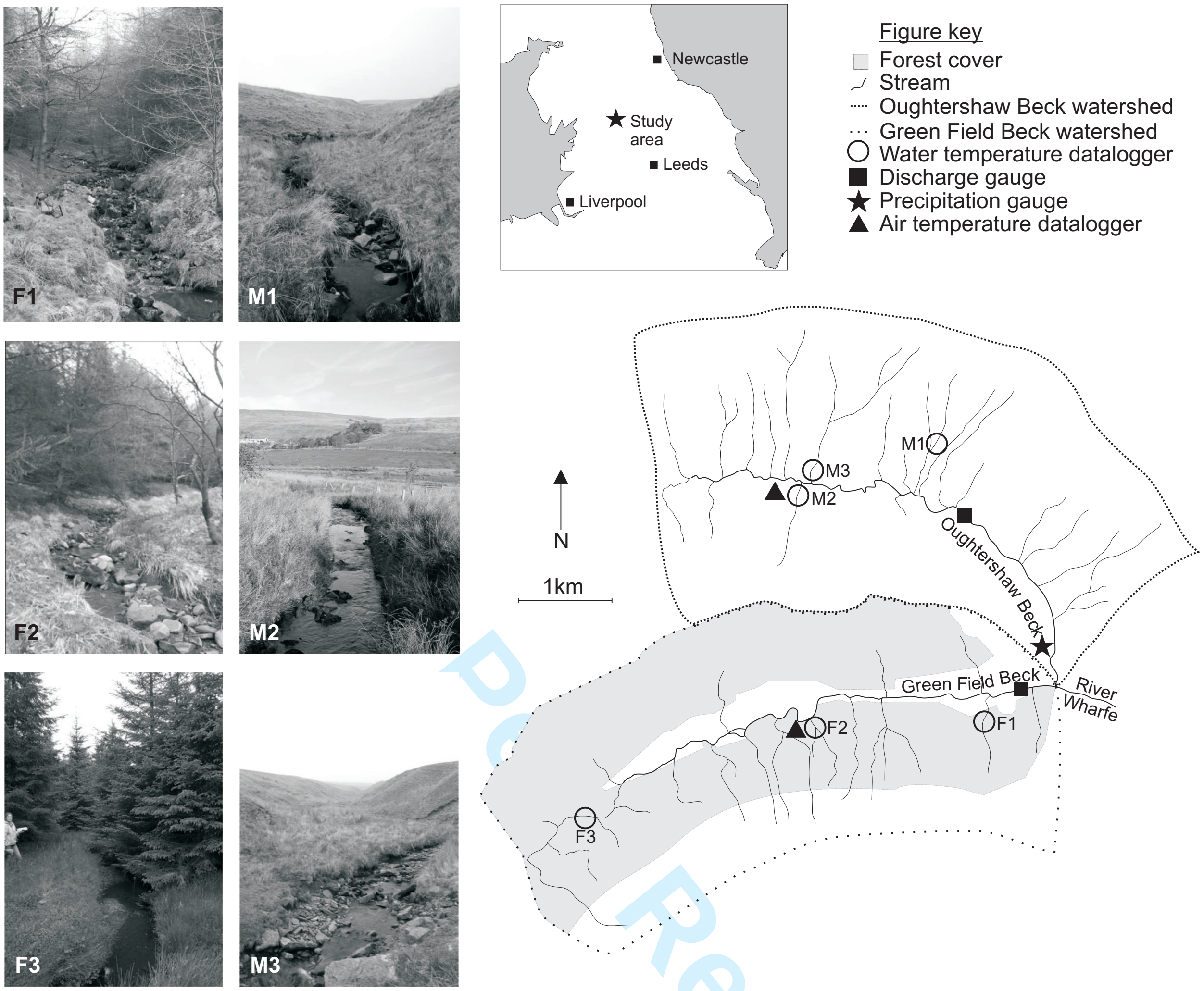
F1
M1
F2
M2
F3
M3
Newcastle
Study area
Leeds
Liverpool
Figure key
Forest cover
Stream
Oughtershaw Beck watershed
Green Field Beck watershed
Water temperature datalogger
Discharge gauge
Precipitation gauge
Air temperature datalogger
N
1km
M1
M3
M2
Oughtershaw Beck
Green Field Beck
River Wharfe
F1
F2
F3