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DOI:
10.1016/j.jhydrol.2024.131163

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Document Version
Publisher's PDF, also known as Version of record

Citation for published version (Harvard):
Dugdale, SJ, Malcolm, IA & Hannah, DM 2024, 'Understanding the effects of spatially variable riparian tree planting strategies to target water temperature reductions in rivers', *Journal of Hydrology*, vol. 635, 131163. https://doi.org/10.1016/j.jhydrol.2024.131163

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Download date: 19. May. 2024

Journal of Hydrology 635 (2024) 131163

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Research papers

Understanding the effects of spatially variable riparian tree planting strategies to target water temperature reductions in rivers

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ARTICLE INFO

This manuscript was handled by Sally Elizabeth Thompson, Editor-in-Chief, with the assistance of Giulia Vico, Associate Editor.

Keywords:
River temperature
Climate change
Tree planting
Process-based model
Riparian shading

ABSTRACT

Climate change is increasing river temperature globally, altering the thermal suitability for iconic cold-water adapted fishes. In regions with low tree cover, the impacts of projected climate change on river temperature will be particularly pronounced due to limited shading of the channel. Reforestation of the riparian corridor is thus increasingly being used to shade rivers and offset projected increases in water temperature. However, tree planting can be expensive and logistically challenging, meaning that there is a need to develop guidance to prioritise tree planting where it can deliver greatest benefits.

In this study, we use a process-based stream temperature model to simulate the likely effects of a real-world tree planting scheme recently implemented on the Baddoch Burn, a tributary of the Aberdeenshire Dee, Scotland. Our results show that, when mature, ~3 km of recent tree planting will increase effective shading in the lower reaches of the Burn from 22% to 47%, delivering a ~1.5 °C decrease in maximum summer stream temperature in comparison to the present-day baseline. We subsequently systematically simulate riparian tree planting in different locations and configurations to determine how and where riparian planting produces and optimal stream temperature response. Our results highlight that different spatial configurations of planting (in terms of length, number, location upstream and spacing between planting zones) can have a considerable impact on stream temperature outcomes, but optimal temperature reductions are generally achieved through planting longer and/or more numerous strips of woodland in upstream reaches, where effective shade is maximised (due to reduced channel width) and where water volumes and residence times mean that impact of reduced solar radiation is greatest.

Our investigation not only highlights the extent to which a real-world tree planting scheme will likely deliver summer stream temperature reductions, but also underscores the importance of planting configuration for delivering a temperature reduction in a desired location. Overall, our results provide useful information for river managers and practitioners to develop appropriate riparian shading schemes to combat climate change-driven stream temperature warming.

1. Introduction

Global river temperatures have increased steadily since the middle of the 20th century (Wanders et al., 2019). Under future climate change, these trends are expected to continue, particularly in temperate and northern latitude river basins (Pohle et al., 2019; Hardenbicker et al., 2017; Isaak and Rieman, 2013; van Vliet et al., 2016). Warming river temperature regimes in these regions will alter their thermal suitability for freshwater and diadromous fish (Dugdale et al., 2018a; Isaak et al., 2018; Muñoz-Mas et al., 2016; Myers et al., 2017), potentially changing the distribution and survival of iconic salmonid species across their native range (Nicola et al., 2018; Sundt-Hansen et al., 2018; Thompson et al., 2012). In regions with strong grazing pressures and thus low riparian tree cover, the impacts of projected climate change on river temperature could be particularly pronounced due to low shading of the river channel (eg. Ghermandi et al., 2009; Hester and Doyle, 2011; Moore et al., 2005). This is the case in Scotland, where high water temperature events associated with low flow conditions in exposed river

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https://doi.org/10.1016/j.jhydrol.2024.131163
Received 3 July 2023; Received in revised form 8 March 2024; Accepted 18 March 2024

reaches are increasingly a cause for concern. Indeed, recent modelling by Marine Scotland (Jackson et al., 2020) suggests that during the 2018 European heatwave, 69% of Scottish rivers (Marine Scotland, 2019) exceeded 23 °C, the threshold for thermal stress in Atlantic salmon (Breau et al., 2011; Corey et al., 2020).

Increasing concerns over the status of Atlantic salmon stocks in Scotland (Chaput, 2012; Morton et al., 2016; Malcolm et al., 2023; Marine Scotland, 2022) have led to the development of a Wild Salmon Strategy which aims to protect and restore salmon populations and the habitats they depend on. Thermal habitat and lack of natural riparian vegetation (resulting from both large-scale historical deforestation and contemporary land management practice, see Bishop et al., 2018; Robbins and Fraser, 2003) are noted as key pressures in the strategy. As such, reforestation of the riparian corridor with pre-deforestation native tree species is an increasingly common management action to offset projected increases in water temperature by reducing solar radiation receipt at the stream surface (Bowler et al., 2012; Davies-Colley et al., 2009; Kristensen et al., 2015). However, riparian tree planting can be expensive and logistically challenging in remote environments, especially where there are contrasting land management goals (eg. where fencing is required to combat high grazing pressures). There is therefore a need to deepen understanding of the likely consequences of riparian tree planting on thermal regimes and refine guidance as new knowledge emerges.

Much recent research has focused on quantifying the degree to which riparian tree cover moderates river temperature extremes (the 'shading effect'; eg. Dugdale et al., 2018b; Kalny et al., 2017; Wondzell et al., 2019) and/or the circumstances under which this shading effect is maximised (eg. Garner et al., 2017; Johnson and Wilby, 2015; Rutherford et al., 2018; Rutherford et al., 2023; Jackson et al., 2021a). When coupled with data from large-scale river temperature monitoring networks (eg. Boyer et al., 2016; Isaak et al., 2017; Jackson et al., 2016) and sophisticated spatio-temporal statistical models of river temperature (e.g. Jackson et al., 2018), these data are being used to develop guidance for riparian tree planting initiatives at large scales (eg. Jackson et al., 2021a) with a view to maximising the stream temperature impact of current (riparian) reforestation programmes.

At smaller (ie. whole-river and sub-basin) scales, process-based stream temperature models are increasingly being used to support river management decision making (eg. Butcher et al, 2010; Abdi et al., 2021; Guzy et al., 2015) by simulating the effects of shading (eg. Abdi et al., 2020a; Beaupré et al., 2020; Fabris et al., 2018). Unlike their statistical counterparts, which excel at predicting and characterising stream temperature across large scales (eg. Daigle et al., 2019; Detenbeck et al., 2016; Jackson et al., 2018; Marsha et al., 2020) or from limited input data (eg. Piotrowski and Napiorkowski, 2019; Rabi et al., 2015; Toffolon and Piccolroaz, 2015), process-based models are particularly useful for testing tree planting scenarios due to their ability to simulate changes in incoming solar shortwave energy (and to a lesser extent, longwave and turbulent fluxes) caused by the addition or removal of tree cover (eg. Baker and Bonar, 2019; Abdi et al., 2020b; Ishikawa et al., 2021) and the cumulative effects of this on advected heat. However, previous investigations using process-based models have typically focused on either developing localised, site-specific guidance on riparian shading effects (eg. DeWalle, 2008, 2010; Garner et al., 2017; Rutherford et al., 2023) or larger-scale idealised or simplified tree planting scenarios (eg. Jackson et al., 2021a; Trimmel et al., 2018; Wondzell et al., 2019), with less attention paid to a) forecasting the outcomes of real-world riparian reforestation programmes that are currently underway, b) learning from these early-adopter programmes to refine planting best-practise or c) using this information to develop guidance for optimised tree planting at intermediate (ie. sub-catchment) scales with different management objectives (ie. targeted vs. overall temperature reductions). Indeed, planting initiatives in parts of Scotland are already starting to drive reforestation of riparian corridors (eg. Drainey, 2012; Shanks, 2020), but the majority of these planting initiatives lack modelling studies to assess their effectiveness (in terms of stream temperature response), propose potential enhancements (where necessary) and better understand the complexities of balancing tree planting against other competing interests.

In light of these research gaps, this paper details the results of a process-based modelling study to assess the likely effects of recent riparian tree planting on river temperature and thermal suitability for salmonids in the Baddoch Burn, a tributary of the Aberdeenshire River Dee, Scotland, that has undergone bankside riparian tree planting over the last decade. The overall aim of our investigation was to simulate the response of stream temperature to recent tree planting carried out in the riparian zone and gain insights into how the specific configuration of tree planting engenders a given stream temperature response. Using the Heat Source model (Boyd and Kasper, 2003), we first simulate current stream temperature within the Baddoch under low flow/high temperature events during the summers of 2016 and 2017. We then use the model to simulate likely stream temperature for similar meteorological conditions following the full establishment of the replanted riparian forest. Finally, we systematically iterate the model with planting arranged in different locations and configurations, to determine whether a similar planting resource deployed differently could have produced alternative temperature outcomes, and whether/how additional planting could further reduce maximum stream temperature. Our specific objectives were to:

1. Calibrate a process-based stream temperature model on the Baddoch Burn capable of simulating stream temperature under recent low flow conditions;
2. Quantify the likely effect of recent tree planting (at maturity) on mean and maximum stream temperatures;
3. Systematically simulate the effects of alternative planting configurations to assess how they interact to drive optimal stream temperature responses, assuming no spatial constraints on the location of planting.

Our study provides insights into how well recent riparian planting is likely to moderate high temperature events in an Atlantic salmon spawning stream that supports an imperilled spring salmon population in a catchment that is susceptible to low flows and thermal extremes. More broadly, our findings provide generalised guidance for river managers looking to optimise tree planting to reduce stream temperatures. Our results thus contribute to the growing body of evidence helping policy makers and river managers to develop adaptation strategies for rivers under global climate and land-use change.

2. Methodology

2.1. Study site

We conducted our study in the Baddoch Burn, an upland Atlantic salmon spawning stream in the Cairngorm Mountains, Scotland (Fig. 1). The Baddoch catchment drains an area of ~23 km^2 into the Aberdeenshire River Dee via its confluence with intermediate tributary the Clunie Water at 56.933N, 3.420W. Elevation in the catchment ranges from 410 to 975 m ASL and land-use is dominated by open heather moorland and rough grassland managed primarily to support traditional highland sporting activities (eg. deer stalking, grouse shooting). Geology in the catchment is predominantly composed of low permeability quartzite and schist bedrock overlain by diamicton and glaciofluvial superficial deposits (Armstrong et al., 2016). Hydrometeorological conditions are typical of the eastern Highlands of Scotland, with a mean annual air temperature of 6.7 °C and mean annual precipitation of 1427 mm recorded in the lower reaches of the Burn between 2014 and 2018. Mean annual discharge is ~0.92 m^3 s^{-1}, with a precipitation and snowmelt-driven hydrological regime comprising high flows between autumn and spring and lower discharge in the summer.

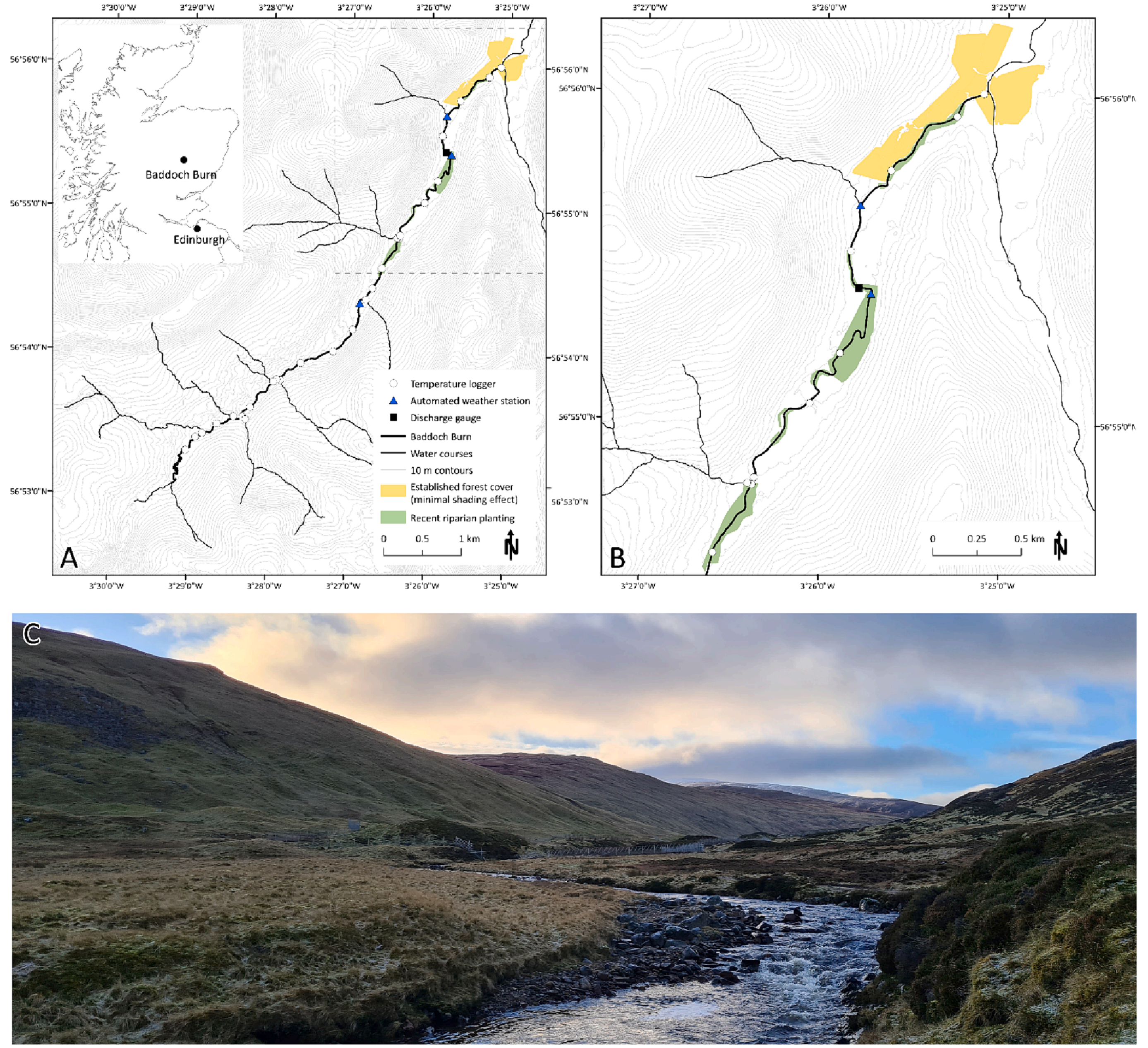


Fig. 1. (A) Baddoch Burn with location of monitoring equipment marked. River temperature model implemented on 7.65 km section between upstream-most and downstream-most temperature loggers. (B) Downstream section of Baddoch Burn showing detail on recent riparian planting activities (green polygons). Note that older established forest cover (yellow polygons) is set back from stream and has minimal shading effect on stream channel. (C) Photo of Baddoch Burn showing current open heather moorland/grassland terrain and general lack of tree cover. Photo credit: Iain Malcolm.

There is currently no mature tree cover in the catchment, aside from a ~800 m strip of commercially-planted conifer woodland within the lowermost reach of the Baddoch (immediately upstream of the confluence with Clunie Water. As a result, there is very little riparian shading present within Baddoch Burn, and even in the lower reaches where forest cover exists, trees are located on the north-west bank of the stream and set back from the channel by ~5–10 m, limiting their effect in terms of shading (see Dugdale et al., 2020). However, given that stream temperature in summer often approaches or exceeds literature-defined thresholds (see Jonsson and Jonsson, 2009) for thermal stress for Atlantic salmon and brown trout (Jackson et al., 2021b), there is a requirement to increase shading to reduce river temperature, especially given climate change projections indicating substantially drier and hotter summers by 2070 (Met Office, 2022).

As a result, the Dee Catchment Partnership (a multi-stakeholder initiative involving fisheries and river management organisations, local and national government agencies, regulators, charities and utilities providers) has been planting trees along the Baddoch Burn since 2013 as part of several broader initiatives led by the River Dee Trust and District Salmon Fisheries Board (eg. *Upper Dee Riparian Woodland Restoration Scheme* and *One Million Trees Project*; Carrell, 2022). This new tree planting, currently consisting of ~3 km total length of ~1 m tall native (eg. birch, alder, willow and rowan) saplings, is predominantly within the critical 5 m riparian buffer zone immediately adjacent to the stream (Fig. 1). The location of these planting zones in the Baddoch's middle and lower reaches is targeted at moderating high stream temperatures in the areas of the catchment supporting the greatest numbers of juvenile Atlantic salmon (predominantly lower reaches near to the confluence), where stream temperatures are also known to be highest (Jackson et al., 2018).

2.2. Stream temperature model

We used a modified version of the Python implementation of Heat Source 9.0.0.b19 (available from https://github.com/DEQrmichie/heatsource-9) to model spatio-temporal stream temperature patterns in the ~7.65 km long Baddoch Burn (Fig. 1). Heat Source is a process-based stream temperature model that calculates temperature at as a function of incoming and outgoing energy fluxes represented by:

$$H_{total} = H_{sw} + H_{lw} + H_e + H_s + H_b + H_a \tag{1}$$

where H_{total} represents the total energy gain or loss at a given river channel node, H_{sw} is solar shortwave radiation flux, H_{lw} is longwave radiation flux emitted from the atmosphere and adjacent terrain/vegetation, H_e is latent energy flux, H_s is sensible energy flux, H_b is energy flux resulting from conduction with the river bed, and H_a is advective energy flux related to inputs from tributaries or groundwater (all in W m^{-2}). Heat Source subsequently calculates the resulting stream temperature at each model node and timestep as a function of H_{total} acting upon a mass of water of given volume, density and velocity at each model node and timestep. Heat Source contains routines to estimate the various terms in Eq. (1) as a function of input hydrometeorological and hydromorphic data and the latitude, longitude, stream azimuth and date/time (for H_{sw}) based on a series of physically-based and semi-empirical equations (see Boyd and Kasper, 2003; Trimmel et al., 2018 for full details). However, with a view to improving model accuracy, we modified the source code to allow inputs of $H_{sw,}$ H_{lw} and H_b from field observations.

Heat Source also contains routines capable of simulating the attenuation of radiative fluxes (and to a lesser extent, turbulent fluxes) by riparian tree cover. This is achieved by inputting data relating to tree height and canopy density at predetermined locations within the riparian zone. Heat Source then uses these data to determine the position of the sun relative to the stream at each model node/timestep and thus calculate whether incoming radiation (direct and diffuse H_{sw}) will be intercepted by trees of a given height. When, at a given timestep, the sun falls behind vegetation, direct H_{sw} is calculated via the Beer-Lambert law, which computes the absorption of light (and thus, the reduction in H_{sw}) by trees it travels through a given distance and density of tree canopy at a given solar elevation angle before reaching the stream's centre. Diffuse H_{sw} received at the stream channel is estimated based on a given node's view-to-sky (VTS). VTS is the fraction of the hemisphere above each node that is free of canopy, and is calculated by determining the presence and density of the tree canopy across the hemisphere based on the angle and azimuth of vegetation in the model node's riparian zone. Heat Source ordinarily only allows input tree cover to be located on land, meaning that the area immediately above the stream surface would not normally be shaded. However, it contains routines that simulate the effect of overhanging vegetation through the entry of a value describing the distance and canopy density of an overhanging 'zone' in which the riparian canopy extends over the stream channel. This effectively means that even when the sun is at high elevations (ie. around midday), direct and diffuse H_{sw} will still be attenuated if a given ray of light traverses this overhang 'zone'. Although the effect of overhanging vegetation in wide rivers is generally small, it has a greater effect in relatively narrow watercourses such as the Baddoch Burn, where overhanging vegetation will (at maturity) likely cover a notable proportion of the channel width. We therefore chose to simulate an overhang distance similar to that found in similar nearby streams with existing tree cover (see Dugdale et al., 2020 and section 2.3.4) to ensure that our model accounts for the (increasing) importance of overhanging vegetation as recently planted tree cover reaches maturity. Heat Source also contains routines that account for the effect of topographic shading on the stream channel which function in a similar manner, taking nearby ground elevations measured from an input digital terrain model to estimate the locations and times where/when the stream is shaded by nearby high ground. Thus, if a reach of stream is already shaded by topography, only the diffuse portion of H_{sw} will be further attenuated by the presence of riparian vegetation, as direct H_{sw} will already have been blocked by topography. For more detail on these shading routines, we refer the reader to Boyd and Kasper (2003), Trimmel et al. (2018), Dugdale et al. (2019, 2020) and the model's source code.

Riparian tree cover also has secondary impacts on water temperature as lower wind speeds and elevated humidity in forested areas can reduce losses from turbulent heat fluxes (ie. lower H_e and H_s; Hannah et al., 2008; Dugdale et al., 2018b). Heat Source also attempts to account for this impact by simulating the reduction in wind velocity caused by friction from tree cover. This is achieved by applying the Prandtl–von Karman universal-velocity distribution law (Dingman, 2002) to the input tree height values to estimate the reduction in wind speed (and thus turbulent fluxes) under trees of a given height.

2.3. Model input data

2.3.1. Meteorological and heat flux data

Data needed to implement Heat Source on the Baddoch Burn were acquired from a mixture of field observations and GIS/remote sensing. Meteorological data required by the various energy flux routines (see Boyd and Kasper, 2003) were recorded by 3x automated weather stations (AWS), two located in the lower reaches of Baddoch Burn (one outside and one within the newly-planted tree cover zone) and one located further upstream (Fig. 1) with a view to capturing spatial variability in meteorological data. Each AWS was programmed to record air temperature (Ta; °C), relative humidity (RH; %), wind speed (WS; m s^{-1}), solar shortwave radiation and net radiation (all W m^{-2}) at 2 m above the channel (at base flow) with a 15-min sampling frequency. Bed heat flux measurements (also W m^{-2}) were recorded by a heat flux sensor installed approximately 5 cm below the bed. The specific instrumentation and setup used at each AWS were similar to those reported by Hannah et al (2008). Cloud cover values required by Heat Source were calculated at each AWS as:

$$CC = \sqrt{1.54 \bullet \left(1 - \frac{H_{sw,observed}}{H_{sw,potential}}\right)} \tag{2}$$

where $H_{sw,received}$ and $H_{sw,potential}$ were the shortwave radiation observed at each AWS and the maximum shortwave radiation possible under a cloudless sky respectively (see Bond et al., 2015). Wind function coefficients required by Heat Source for computation of turbulent fluxes were held as calibration parameters and optimised during model calibration (see section 2.4) within the bounds of values previously reported in the literature.

2.3.2. Stream temperature data

Each AWS incorporated a Campbell Scientific 107 thermistor probe installed within the channel that was used to record stream temperature (T_W; °C) adjacent to the weather station. These were supplemented by another thermistor attached to a Marine Scotland Science (MSS) gauging station and a further 26 TinyTag Aquatic 2 data loggers installed at strategic locations within the Baddoch Burn and major tributaries (Fig. 1) between early summer 2016 and 2018. All thermistor probes and loggers were corrected to a true temperature reference, cross-calibrated (to give an accuracy of ±0.02 °C), and programmed to record temperature at the same 15-minute interval used for the AWSs (for further details see SRTMN web pages; Jackson et al. 2021b). Care was taken to install loggers/probes near to the thalweg (well-mixed zone) to avoid bias from thermal stratification; loggers were also inserted into PVC tubing to shield against radiative biases. Data for most logger sites were available for the entire period, although data for some sites were lost following high flow events in summer 2016. In total, temperature data from 9 of the loggers installed at the upstream limit of the Baddoch Burn and within tributaries were used to provide water temperature boundary conditions for the upstream-most model node and for incoming tributaries. Of the remaining 21 loggers (ie. those installed in the Baddoch Burn's main stem), 18 recorded data during both the calibration and validation periods (see section 2.4), and were thus held back for model calibration/validation, while three loggers yielded incomplete datasets and were not used.

2.3.3. Hydrometric data

15-min discharge data needed to run Heat Source came from a MSS gauging station located in the lower reaches of Baddoch Burn. Flows measured at this gauging station were scaled by basin area to provide discharge boundary conditions for the Baddoch Burn's main stem and eight of its tributaries. All other tributaries were at least an order of magnitude smaller (based on flow accumulation), and it was therefore deemed unnecessary to provide further boundary conditions for these very minor contributions. Because of uncertainty surrounding tributary discharges calculated using scaling approaches such as this, we allowed the tributary discharge to vary between 60 and 100% of their basin area-estimated value during model optimisation (see section 2.4) in order to test the sensitivity of the model to minor changes in tributary inflow. Main stem velocities computed from the resulting discharge by Heat Source's hydraulic model component were compared against spatially-explicit values measured in the field using a Valeport 801 electromagnetic flow meter and top-set rod, and found to be in good agreement (observed: 0.157 ± 0.055 m s^{-1}; simulated: 0.162 ± 0.028 m s^{-1}).

2.3.4. Physiographic and hydromorphic data

Spatially-explicit channel azimuth, bed width, gradient and topographic inputs required by Heat Source were derived from remote sensing and GIS data. Channel azimuth is automatically calculated by Heat Source for each model node based on its input latitude and longitude. Channel bed width was measured from aerial photography of the Baddoch Burn acquired in 2014 during low flow conditions which were representative of widths during model calibration/validation periods (accompanied by similarly low flows). Heat Source subsequently uses these widths (alongside hydrometric inputs) to estimate simplified trapezoid channel cross-sections based on Manning's equation (see Boyd and Kasper, 2003) and thus simulate changes in river stage as a response to discharge. Although this represents a simplification of true channel bathymetry, this nonetheless allows the model to account for the impact of longitudinal variability in width:depth ratio on the stream's energy budget and thus temperature. Channel gradient and near-stream topography (needed for the calculation of topographic shading) were computed from a 5 m resolution digital terrain model (DTM; Ordnance Survey, 2017) of the study area.

Data on the location of established tree cover (see Fig. 1) needed to calculate the impact of existing riparian shading were derived from OS MasterMap polygons (Ordnance Survey, 2018); within these polygons, we assumed a uniform tree height of 10 m (similar to LiDAR-calculated heights for other woodland in the region; Dugdale et al., 2020), a canopy density of 70% (based on literature-derived estimates optimised in a previous modelling study; see Dugdale et al., 2019). An overhang value of 2.5 m was used to simulate the shade cast by overhanging vegetation (once mature). This value approximates half of the crown diameter at maturity for tree species recently planted within the Baddoch Burn (based on allometric data for these species; Evans et al., 2015; Pretzsch et al., 2015), and assumes that once mature, trees will overhang 87% of the average channel width of 5.7 m.

Heat Source also requires inputs of a range of further hydromorphic parameters (eg. sediment thermal conductivity, hyporheic layer thickness, Manning's roughness coefficient; see Trimmel et al., 2018 for full list) which are difficult to measure in the field (particularly in terms of their spatial variability), but can nonetheless influence stream temperature (eg. cooling from hyporheic inflows; eg. Leach et al., 2023). As such, these values were held as spatially-constant model parameters and allowed to vary within a range of plausible literature-derived values during model calibration (see section 2.4).

2.4. Baseline model implementation and calibration/validation

Heat Source was calibrated on a four-week period in summer 2017 (9th July–6th August) characterised by sustained high air temperature for the location (mean, minimum and maximum of 12.0 °C, 1.7 °C and 20.2 °C respectively at downstream-most AWS). Our specific calibration period was chosen with the intention of simulating temperatures under the sustained warm weather/low flow conditions during which tree shading has its greatest impact on mitigating temperature extremes that are stressful to fish. Given that our specific interest is in understanding how shading might mitigate similar elevated stream temperature events if they occur in future, we determined that a model calibration period focused on warm conditions would yield an optimal parameter set for our specific purposes. We avoided using a longer calibration period as the relative infrequency of longer windows of warm weather in the study location means that a longer timeseries would have encompassed frequent notable cool, high flow events, and thus biased our model towards these cooler, wetter conditions. Furthermore, a four-week period was chosen with a view to achieving an acceptable compromise between the time needed for model calibration (approximately 25 mins per model run on an x64 desktop workstation with a 3.60 Ghz CPU and 32 Gb RAM) and the length of the calibration dataset. A downstream resolution (node spacing) of 50 m and timestep of 1 h was chosen to maximise simulation of spatio-temporal river temperature patterns while again leaving model runtime practical. During model calibration, the parameters detailed in section 2.3 (see Table 1) were first manually adjusted to explore the range of physically-plausible parameter combinations that generated a reasonable root mean square error (RMSE) between simulated and observed temperature recorded at 21 locations in the Baddoch Burn's main stem. Inspection of the results of this initial manual calibration phase highlighted the two wind function coefficients and the hyporheic layer thickness value as among the most sensitive parameters, highlighting the potential role of evaporative cooling and hyporheic flow on the temperature dynamics of the Baddoch Burn. This exercise also indicated that our model was able to achieve reasonable results while keeping all parameters within realistic limits (see Table 1) similar to those reported in the literature for other stream temperature modelling studies, providing confidence in our model's basic setup. Following this first calibration phase, the model was optimised by using Latin Hypercube (LHC) sampling to generate 10,000 parameter combinations from across the parameter space determined by manual calibration, and a Monte-Carlo approach was then used to optimise the calibration by simulating each of these combinations. Given that our parameter space is relatively tightly defined by the range of physically-plausible values and that our initial manual calibration phase highlighted the more sensitive of these parameters, this LHC-based optimisation approach was deemed best-suited to achieving a reasonable calibration while leaving optimisation runtime within acceptable limits.

Following selection of the parameter set that produced the best model RMSE, the model was validated by re-running it with hydrometeorological data from a similarly warm four-week period in summer 2016 (21st June–19th July; mean, minimum and maximum of 11.7 °C, 2.8 °C and 22.6 °C respectively at downstream-most AWS), and the model's validity assessed by comparing the RMSE values yielded by the calibration and validation periods. Note that the model was calibrated on summer 2017 and validated on summer 2016 (rather than vice-versa) because high flows during early summer 2016 caused data to be lost from 3 logger sites; calibration was carried out using the more complete of the two datasets to maximise model quality. Once calibrated, the same parameter set was used for all subsequent model runs (see section 2.5).

Table 1
Parameter set for optimised model of Baddoch Burn. Calibration parameters given in unshaded cells, fixed parameters given in grey cells.

Parameter	Units	Final optimised parameter	Calibration range
Sediment thermal conductivity	W m^{-1} $°C^{-1}$	1.36	0.8 – 1.8
Sediment porosity	unitless	0.40	0 - 1
Manning's roughness coefficient	s^{-1} $m^{1/3}$	0.25	0.1 – 0.5
Thickness of hyporheic layer	m	0.61	0 – 1
Hyporheic exchange	%	2.02	0 – 15
Wind function coefficient *a*	mb^{-1} m s^{-1}	1.61×10^{-9}	$0.5 \times 10^{-9} – 3.0 \times 10^{-9}$
Wind function coefficient *b*	mb^{-1}	1.27×10^{-9}	$0.5 \times 10^{-9} – 3.0 \times 10^{-9}$
Basin size scaling factor	%	91%	60 – 100
Sediment thermal diffusivity*	m^{-2} s^{-1}	6.40×10^{-3}	-
Deep alluvium temperature*	°C	9.00	-
Canopy density†	%	70%	-

* Note that sediment thermal diffusivity and deep alluvium temperature were held as fixed parameters as the introduction of observed bed conduction values into Heat Source negates the need to optimise these parameters (but Heat Source nonetheless requires values to be entered in order to run).
† Canopy density value based on literature-derived estimates optimised in a previous study; see Dugdale et al., 2019.

2.5. *Current and hypothetical tree planting scenarios*

In addition to the 2017 base model, we developed a series of temperature models to a) understand how stream temperature will respond to recent tree planting activity in the Baddoch Burn when tree cover is mature (under low flow conditions similar to summer 2017), b) assess whether the location of tree planting could have been further optimised to further reduce warming, assuming a fixed resource (length of planting), but with total flexibility in potential planting locations, and c) identify how and where additional tree planting could further reduce stream temperature, were further planting resource available.

2.5.1. *Impact of recent riparian planting*

To assess the potential impact at maturity of recent tree planting activities carried out as part of the Upper Dee Riparian Woodland Restoration Scheme, we parameterised the 2017 model with tree cover data derived from GIS polygons defining the locations of recent tree planting (Fig. 1); GIS polygons were provided by the River Dee Trust. For these data, we again assumed a uniform tree height of 10 m and a canopy density of 70%. The effect of recent tree riparian tree planting on stream temperature was subsequently quantified by examining the difference in mean and peak stream temperature between the 2017 base model and this second model that incorporated tree cover (hereafter referred to as the *recent planting model*).

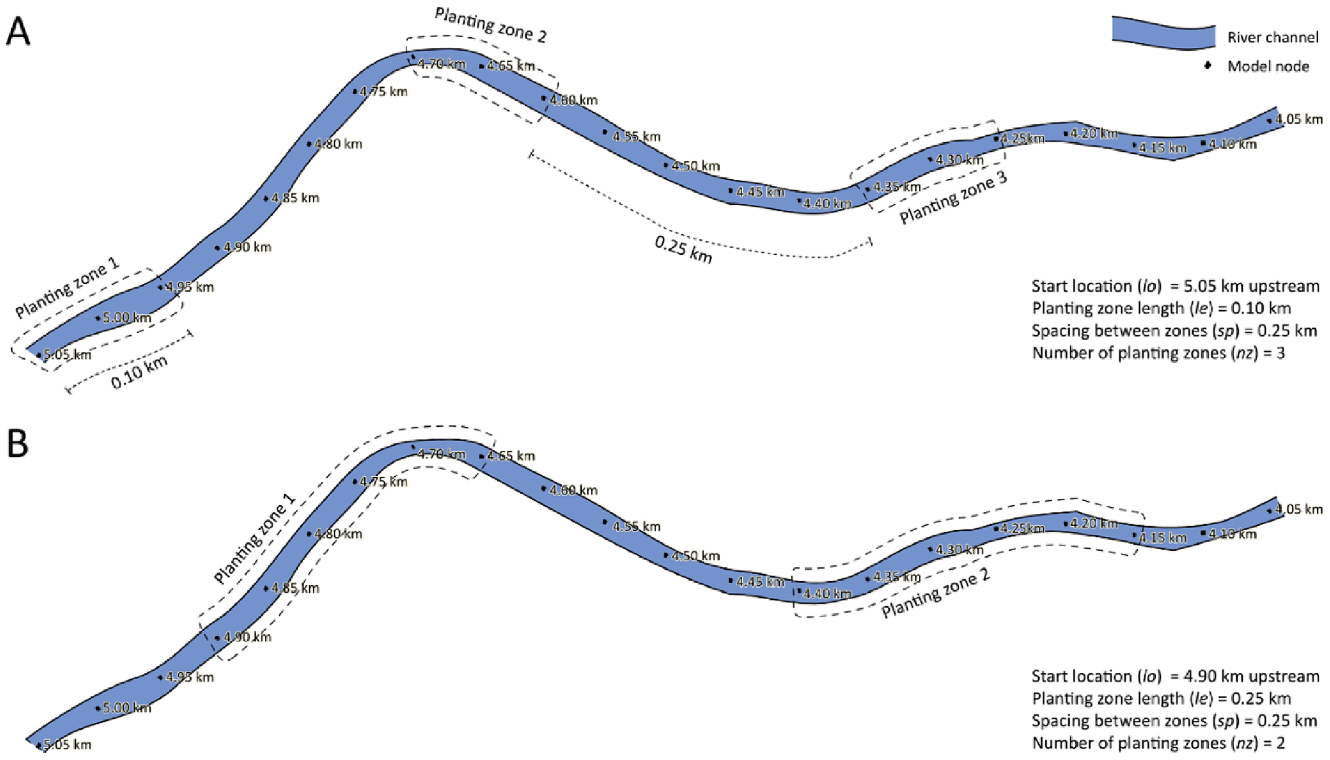


Fig. 2. Example of two different tree planting scenarios modelled for Baddoch Burn showing effect of varying parameters governing the location, extent and no. of planting zones.

2.5.2. Riparian planting optimisation

In order to explore the extent to which the spatial configuration of these recent tree planting zones could have been optimised to further reduce temperature within the Baddoch Burn, and with a view to developing general rules governing the optimum positioning of tree planting, we developed two custom MATLAB functions that iterated the locations of tree cover within the Baddoch Burn and then recorded the resulting impact on stream temperature, as simulated by Heat Source. The first of these functions took the recently planted zones highlighted in Fig. 1 and randomly redistributed them across the 7.65 km length of the Baddoch Burn (but keeping the planting patch dimensions the same), with a view to understanding whether the same total amount of tree planting could have provided improved temperature moderation if distributed differently; in total, we ran 1000 random riparian planting permutations on this basis. These simulations are hereafter referred to as the *random planting optimisation scenarios.*

The second MATLAB function was similar; however, instead of randomly simulating the planting of woodland, here we systematically changed the start location (*lo*) and length (*le*) of hypothetical riparian planting zones, as well as the number (*nz*) of hypothetical planting zones present (Fig. 2) and the spacing (*sp*) between them. These simulations, totalling 1596 unique planting parameter combinations, are subsequently referred to as the *systematic planting optimisation scenarios.* Values used for these planting parameters are given in Table 2. By quantifying the magnitude and distribution of the temperature difference for each of these hypothetical planting scenarios in relation to the 'base' model, these data can provide general insights the effect of riparian shading in different configurations and locations along a river; indeed, the paucity of information on the cumulative temperature effect of multiple tree-lined reaches (eg. Jackson et al., 2021a) means that such data is of particular interest with a view to enhancing current and future riparian planting initiatives.

2.6. Metrics to quantify the riparian shading effect

A range of metrics have previously been proposed for quantifying ecologically-relevant temperature statistics relating to rivers (eg. [seven-day] [average] daily maximum temperature; Beechie et al., 2021; Jackson et al., 2018; Wondzell et al., 2019; temperature/degree hours/days [above a threshold]; Bakken et al., 2016; Dugdale et al., 2018a; variance-based measures; Daigle et al., 2019; Steel et al., 2016). While these metrics are useful for characterising river temperature regimes at broader scales, they are not optimised for understanding the fine-scale spatiotemporal response of stream temperature to varying riparian woodland configurations. As such, we quantified the river temperature response to different riparian shading in several ways.

In the first instance, we calculated the maximum difference in the mean (ΔTw_{mean}) and maximum (ΔTw_{max}) temperature between a given shading scenario and the present date baseline (for the modelled period) using the equations:

$$\Delta Tw_{mean} = \max\left(\overline{Tw_{baseline_{t,x}}} - \overline{Tw_{scenario_{t,x}}}\right) \tag{3}$$

$$\Delta Tw_{max} = \max\left(\max\left(Tw_{baseline_{t,x}}\right) - \max\left(Tw_{scenario_{t,x}}\right)\right) \tag{4}$$

where $Tw_{baseline}$ and $Tw_{scenario}$ refer to the stream temperature at time t and distance downstream x for the baseline model and given tree planting scenarios respectively (both in °C); a positive ΔTw_{mean} or ΔTw_{max} value indicates a reduction in temperature in relation to the baseline model.

Table 2
Specifications of systematic riparian planting scenarios.

Planting scenario parameter	Value
Start location of riparian tree planting zones (*lo*)	Starting at upstream-most model node, then moving downstream by 0.25 km at each iteration
Length of planting zones (*le*)	0.1 km, 0.25 m, 0.5 km, 1.0 km, 2.0 km
Number of planting zones (*nz*)	1–10 zones
Spacing between planting zones (*sp*)	0.25 km, 0.5 km, 1.0 km, 2.0 km

The point of maximum difference often falls near the basin outlet, but shifts around depending on tree planting configuration. However, because the reaches adjacent to the basin outlet are the sites of highest salmonid production (Malcolm et al., 2019), we also report temperature differences at the outlet ($\Delta Tw_{mean,outlet}$ and $\Delta Tw_{max,outlet}$). The outlet temperature is also important in terms of the ability of a smaller sub-basins (ie. Baddoch Burn) to act as thermal refugia for their parent water course or to reduce rates of warming upstream of larger rivers where shading is known to be less effective (Jackson et al., 2021a).

While these metrics provide a location-specific indication of the riparian shading effect, they are unable to summarise the impact of riparian shading across the entire river. Consequently, we also integrated the maximum temperature long profile produced by each simulation to compute its area-under-the-curve (*AUC*), providing a measure of temperature reduction engendered by riparian planting throughout the whole stream (rather than just at a given location). Because this metric does not consider the width of a given channel segment (ie. a narrow cool reach may produce a favourable ΔTw_{mean} or *AUC*, but be of limited ecological relevance to salmonids due to low wetted area), we also computed each scenario's 'wetted area-under-the-curve' (*wAUC*) as the double integral of the temperature long profile (ie. incorporating wetted width (*w*) as well as distance downstream). This measure, in °C km^2, thus allows us to account for wetted area when assessing the relative performance of riparian shading scenarios (ie. the total wetted area affected by a given temperature reduction). *AUC* and *wAUC* are given by:

$$AUC = \sum_{\substack{t=1\\x=1}}^{n}\left(\max\left(Tw_{scenario_{t,x}}\right)\right) \tag{5}$$

$$wAUC = \sum_{\substack{t=1\\x=1}}^{n}\left(\max\left(Tw_{scenario_{t,x}}\right) \bullet w_x\right) \tag{6}$$

where lower (smaller) *AUC* and *wAUC* values indicate greater reductions in stream temperature in relation to the baseline model.

Finally, in order to examine general rules linking a given stream temperature response to the start location (*lo*), length (*le*), number (*nz*) and spacing (*sp*) between riparian planting zones, we used stepwise linear regression fitted between *AUC* and these four planting parameters to understand which generated the strongest stream temperature response. We used R^2 and ΔAIC (Akaike's Information Criterion) to quantify the relative influence of a given planting parameter in controlling stream temperature *AUC*. We used *AUC* for these analyses rather than *wAUC* to isolate solely the stream temperature response to different planting configurations, as *wAUC* would introduce location-specific wetted area biases, reducing the generalisability of the regression results to other water courses.

3. Results

3.1. Base model performance and space–time stream temperature patterns

Following calibration/validation, the Heat Source model was able to reproduce stream temperature in the Baddoch Burn with a good degree of accuracy across the 18 temperature logger sites common to both periods (mean calibration RMSE = 0.98 °C, mean validation RMSE = 1.01 °C). In terms of the spatial distribution of model error, both the calibration and validation datasets show an increase in model RMSE as a

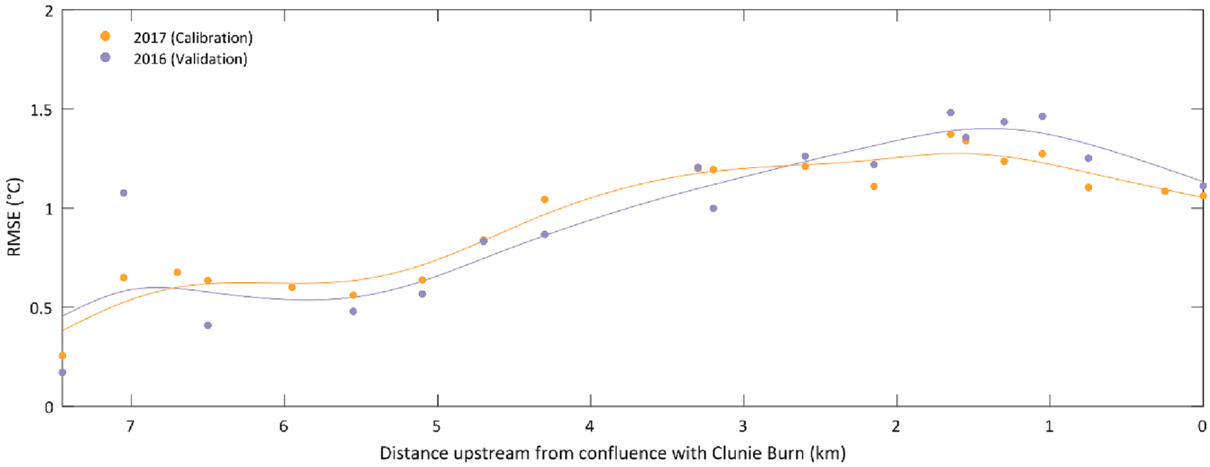


Fig. 3. Streamwise distribution of model error during calibration (2017) and validation (2016) showing eventual stabilisation of RMSE at ~3 km upstream from the confluence. Solid lines indicate smoothed trend (spline fit with smoothing factor = 0.9).

function of distance downstream from the boundary condition at 7.65 km until approximately ~3 km upstream from the Baddoch's confluence where RMSE stabilised (Fig. 3). Higher RMSE values observed at certain sites (eg. 7.05 km in validation dataset and between 1.00 and 2.10 km in both datasets) are likely a function of either 'stranding' of loggers during particularly low flows, insufficient scaling of discharge from tributaries or inadequate process representation/model parameterisation at certain locations; this is discussed further in section 4.4.

Inspection of temporal variability in simulated temperature against observations at selected logger sites (upstream, mid- and downstream; Fig. 4) indicates a moderate systematic negative bias during periods of lower stream temperature and increased discharge. This effect is most pronounced at the mid- and downstream- sites and during higher flow periods (eg. ~21st July 2017) where the model under predicts true stream temperature during night-time lows. However, bias is reduced on warmer days (particularly during low flows), indicating that the model is capable of reproducing high temperature events with a good degree of accuracy.

In terms of simulated spatio-temporal temperature patterns, mean stream temperature within the Baddoch Burn exhibited a relatively weak but persistent downstream temperature increase over the modelled period, with a time-averaged temperature increase of ~0.2 °C km^{-1} recorded by the temperature loggers and reflected in the simulations for the calibration and validation periods (Fig. 5). While the mean downstream temperature profile is relatively stable without notable streamwise fluctuations, close inspection of the data highlight local temperature maxima at ~7.30 km, 6.05 km, 4.25 km and 1.10 km, particularly in the 2017 (calibration) dataset. These maxima occur immediately upstream of the location of several (but not all) tributaries which cause momentary temperature reductions of ~0.5 °C, highlighting the role of relatively minor tributary inflows in reducing peak temperature. In terms of temperature fluctuations not associated with tributaries (eg. temperature 'jump' at ~1.25 km; Fig. 6), inspection of the model's simulated hydraulic and energy balance data reveal that such temperature variations are driven by spatial variability in the channel's width:depth ratio (and to a lesser extent, changes in stream azimuth and the presence of topographic shading), which alters solar radiation receipt and thus the stream's energy budget (see section 2.3.4).

Unsurprisingly, downstream temperature patterns exhibit strong diel and longer-term temporal variability resulting from prevailing hydrometeorological conditions and advected heat, with positive instantaneous temperature trends (ie. temperature difference between upstream and downstream-most model nodes) predominantly recorded during the late afternoon and negative trends chiefly observed during the night-time and early morning. In terms of maximum and minimum downstream trends, a maximum instantaneous temperature difference of +5.3 °C was observed at 15:00 on 18th July 2017 (calibration dataset), following a period of persistent warm dry weather. Conversely, the largest negative trend of −2.1 °C was observed on 18th July 2016 at 17:00 (validation dataset) following a period of cool air temperature and overcast/rainy conditions.

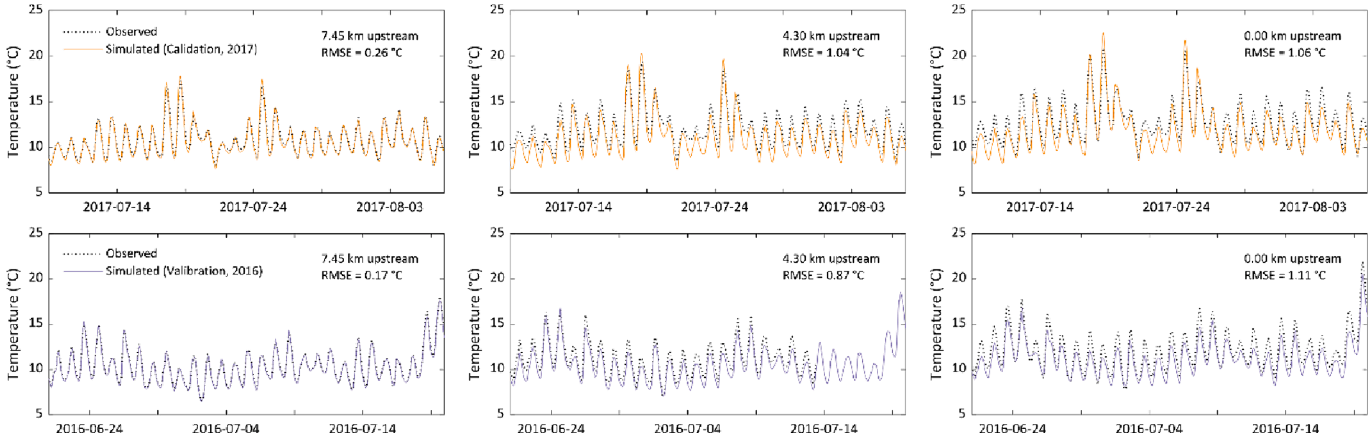


Fig. 4. Simulated vs observed stream temperature at upstream, mid-stream and downstream temperature loggers installed in Baddoch Burn.

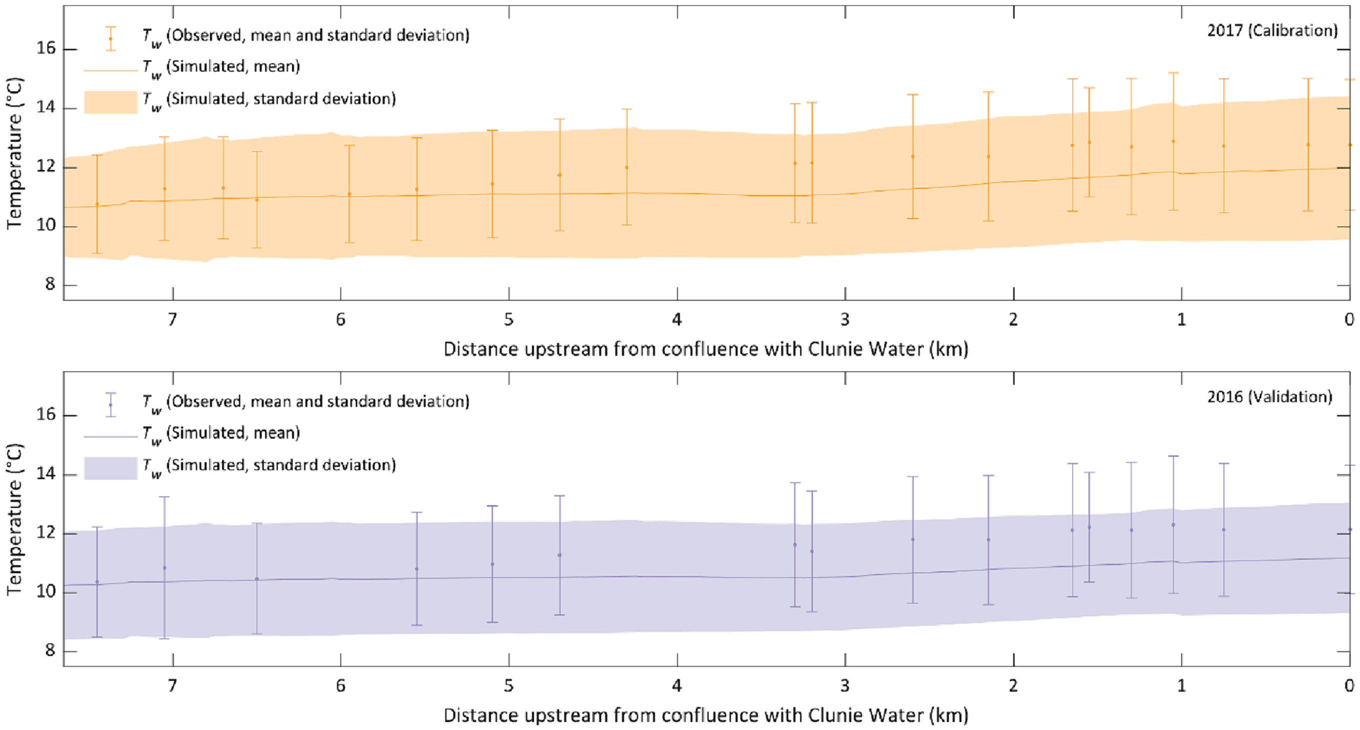


Fig. 5. Downstream temperature long profiles for Baddoch Burn during calibration (2017) and validation (2016) periods. Markers give mean and standard deviation of temperature observed at loggers. Solid line gives time-averaged mean temperature from Heat Source simulation, ribbon indicates temperature standard deviation at each model node.

3.2. Projected shade and stream temperature response to recent tree planting activities

Re-parameterisation of the 2017 Heat Source model with the location of recent tree planting activities reveals the extent of shade generated and thus the amount of stream temperature moderation that might be expected in the Baddoch Burn under similar hydrometeorological conditions once recently planted trees (Upper Dee Riparian Woodland Restoration Scheme) are mature (Fig. 6). Inspection of the time-averaged effective shade (ie. the ratio of potential to received solar radiation at the air–water interface; Boyd and Kasper, 2003) projected under these new riparian tree planting areas indicates a substantial increase in effective shade ($\overline{x} = 47\%$) in comparison to present day values ($\overline{x} = 25\%$), where shading is predominantly derived from local topography rather than tree cover. Indeed, it is noteworthy that recent riparian planting activities have predominantly been carried out in mid- and downstream reaches where current effective shade is particularly low and juvenile salmon production is typically highest due to access constraints in the upper catchment. In comparison, the combination of steeper topography and narrower wetted width means that the more upstream areas of Baddoch Burn (3.90–7.65 km) are already shaded to some extent (~33% effective shade). These upstream reaches are also cooled by the presence of several tributaries which drive transitory reductions in stream temperature, particularly apparent from the maximum temperature profile (Fig. 6b) where the difference between the ambient main stem and cooler tributaries is maximised.

The stream temperature effect generated by this shading generally increases in a downstream direction from the upstream-most planting location, with ΔTw_{mean} and $\Delta Tw_{mean,outlet}$ occurring at the same location (0.44 °C; Fig. 6a; Table 3). Although the mean temperature difference is relatively small, the maximum stream temperature difference in the downstream-most reaches of Baddoch Burn is considerably greater ($\Delta Tw_{max} = 1.52$ °C, $\Delta Tw_{max,outlet} = 1.40$ °C; Fig. 6b; Table 3). Spatial variability in the maximum stream temperature long profile reveals that while the effects of the upstream-most tree planting zone are relatively small (centred at ~4.5 km), the longest tree planting zone located between ~1.25 and ~2.50 km causes a stronger stream temperature response, particularly towards its downstream end, where the difference between the base and recent planting models reaches its maximum. Downstream of this zone, the cooling trend is temporarily interrupted as the stream enters a more open reach. Cool water inputs from a tributary at 1.00 km also further reduce the difference between the base and recent planting models at this point. However, beyond this point, the presence of a final tree planting zone near the Baddoch's confluence causes stream temperature to again start to diverge further below the base model.

3.3. Optimising the riparian shading effect

3.3.1. Random planting optimisation scenarios

Results of the first set of simulations, whereby we randomly redistributed the recent planting zones across other locations in the Baddoch Burn (see section 2.5.2), indicate that the temperature reduction at the furthest downstream model nodes generated by recent planting ($\Delta Tw_{mean,outlet}$ and $\Delta Tw_{max,outlet}$) is close to the maximum that can be delivered by planting the same amount of stream length as that planted under the recent reforestation initiatives in Baddoch Burn (Fig. 7a). However, in terms of a whole-river temperature reduction, the lowest *AUC* produced by the 1000 random planting optimisation scenarios (144.0 °C km; Table 3) indicates that greater overall temperature reductions could have been achieved (Fig. 7a) with the relocation of the same amount of tree planting to the upstream reaches of Baddoch Burn. Under this scenario, planting would have substantially enhanced shading in upstream reaches (≥75% effective shade), leading to a greater temperature reduction ($\Delta Tw_{max} = 2.35$) upstream. However, this result comes at the expense of a smaller temperature reduction at the confluence ($\Delta Tw_{max,outlet}$ 1.04 °C). Conversely, when considering the area of stream over which a temperature reduction applies via the wetted area-under-the-curve (*wAUC*) metric (see section 2.6), the lowest *wAUC* scenario (0.763 °C km^2) indicates that a different shading

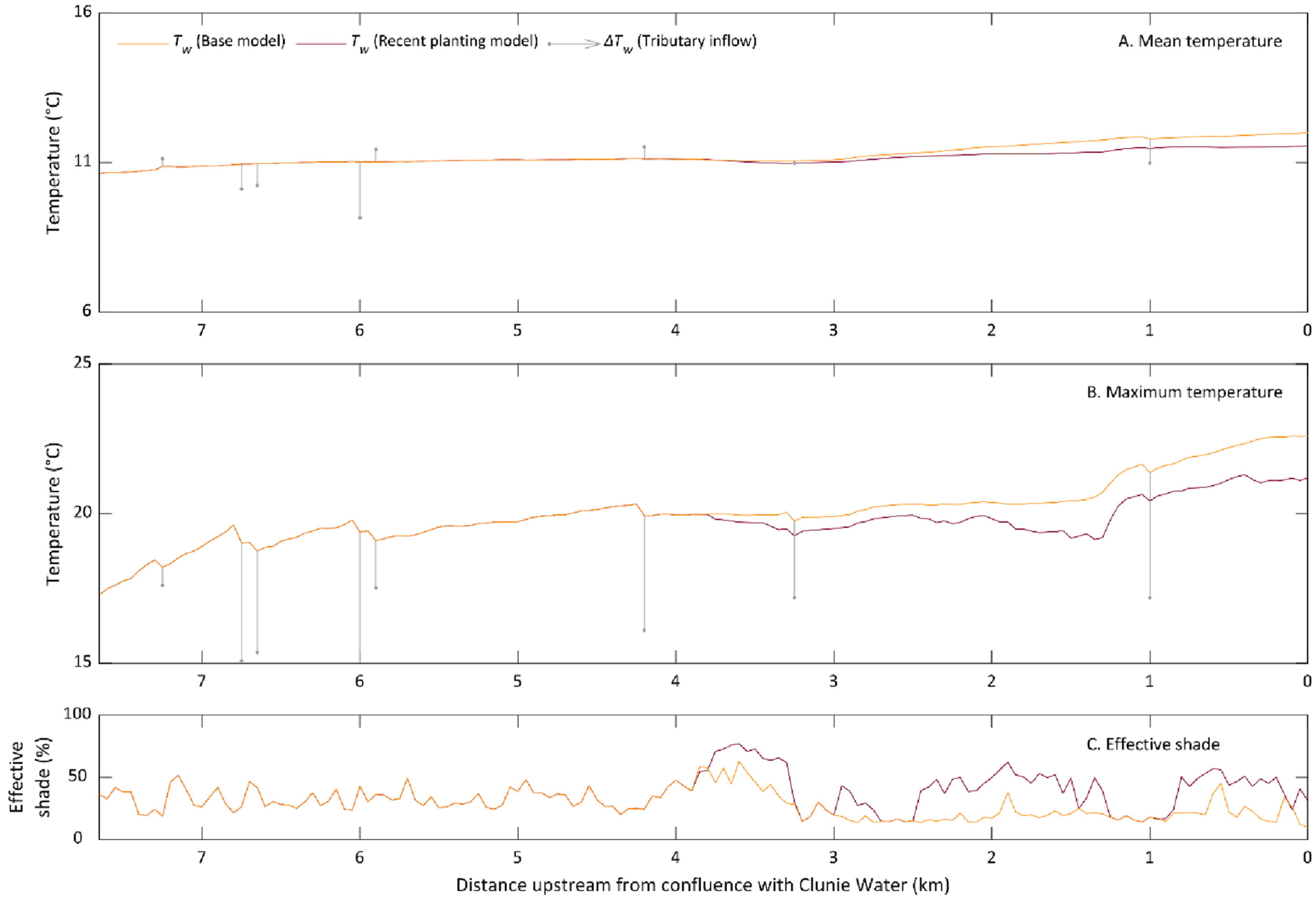
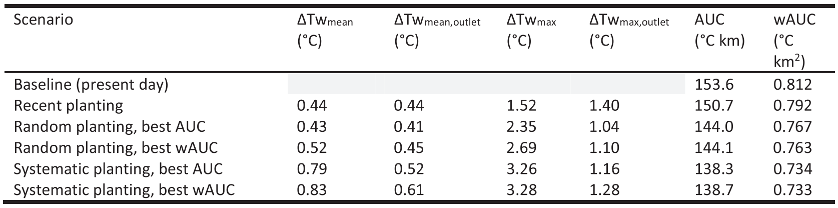


Fig. 6. Time averaged mean (a) and maximum (b) temperature profiles for Baddoch Burn showing difference in stream temperature and (c) effective shade produced by base and recent planting models; both models using hydrometeorological inputs from 2017 calibration period.

Table 3
Riparian shading effect metrics for modelled scenarios.



Scenario	ΔTw_{mean} (°C)	$\Delta Tw_{mean,outlet}$ (°C)	ΔTw_{max} (°C)	$\Delta Tw_{max,outlet}$ (°C)	AUC (°C km)	wAUC (°C km^2)
Baseline (present day)					153.6	0.812
Recent planting	0.44	0.44	1.52	1.40	150.7	0.792
Random planting, best AUC	0.43	0.41	2.35	1.04	144.0	0.767
Random planting, best wAUC	0.52	0.45	2.69	1.10	144.1	0.763
Systematic planting, best AUC	0.79	0.52	3.26	1.16	138.3	0.734
Systematic planting, best wAUC	0.83	0.61	3.28	1.28	138.7	0.733

configuration (ie. one that biases tree planting in more mid-stream locations) might have produced more favourable results in the middle and lower reaches of the Baddoch Burn ($\Delta Tw_{max} = 2.69$), albeit still at the expense of a reduced effect at the confluence ($\Delta Tw_{max,outlet}$ 1.10 °C) where juvenile salmon densities are highest (Malcolm et al., 2019).

3.3.2. Systematic planting optimisation scenarios

Similar spatial effects were observed when we systematically tested the impact of varying riparian woodland enclosure lengths, locations and quantities (Fig. 7b). Here, the scenarios producing the lowest *AUC* and *wAUC* metrics (138.3 °C km and 0.733 °C km^2) indicate that long strips of further tree planting (ie. several strips of 1000 or 2000 m in length) in the middle and upstream reaches would generate a strong temperature reduction in the middle of Baddoch Burn ($\Delta Tw_{max} = 3.26$ and 3.28 respectively). While the lowest *AUC* scenario delivered a somewhat sub-optimal response at the outlet ($\Delta Tw_{max,outlet} = 1.16$ °C), when incorporating wetted area, the best *wAUC* scenario achieved a temperature reduction at the outlet close to the maximum possible for the amount of stream bank planted ($\Delta Tw_{max,outlet} = 1.28$). While this indicates that further temperature reductions in the Baddoch Burn are theoretically possible, it is important to note that in reality, the planting of such long extents of riparian woodland in the Baddoch Burn would not have been practical for a variety of reasons (see section 4.3).

3.4. Quantifying the role of riparian planting configuration

Across all scenarios, optimal temperature outcomes (in terms of *AUC* and *wAUC*) are unsurprisingly achieved through the presence of longer and/or more numerous planting zones (Fig. 8). However, our results also highlight the importance of planting configuration, whereby planting in

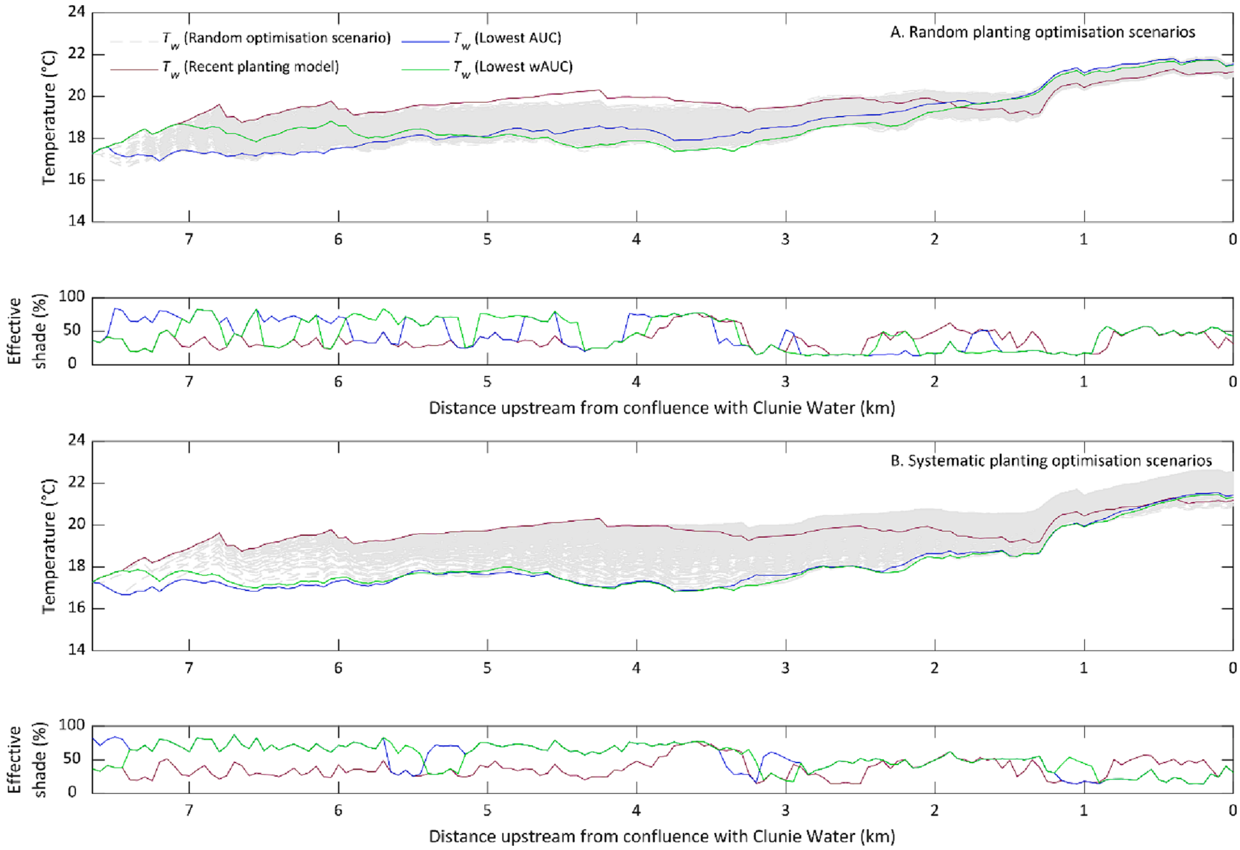


Fig. 7. Time averaged maximum temperature profiles for Baddoch Burn yielded by (a) *random planting optimisation scenarios* and (b) *systematic planting optimisation scenarios*, showing difference in effective shade and stream temperature produced by recent planting models compared to scenarios; all simulations using hydro-meteorological inputs from 2017 calibration period. Optimal scenarios for (a) and (b) given by long profile that yielded lowest AUC (blue line in temperature and effective shade plots) and wAUC metrics (green line in temperature and effective shade plots).

upstream locations produces more favourable results than similar (or even longer) lengths of riparian planting in middle and downstream reaches (Fig. 8). In Fig. 8, particularly strong temperature responses ($AUC < 140$ °C km and $wAUC < 0.740$ °C km^2) were somewhat unsurprisingly associated with long planting zones (several strips of 1000 m or 2000 m length) in the upstream reaches. However, of note is that the total length of planted woodland is only marginally more influential in terms of temperature reduction than the point upstream at which planting is located, regardless of whether or not wetted area (ie. *wAUC*) is taken into account. For example, 5 × 500 m woodland strips starting at 7.65 km upstream generates an *AUC* of 145.4 °C km ($wAUC = 0.776$ °C km^2), whereas planting twice this river length (5 × 1000 m strips), but starting at 6.15 km, yields only a marginally better *AUC* of 143.9 °C km ($wAUC = 0.755$ °C km^2). Overall, this indicates that while increasing the overall amount of riparian woodland reduces river temperature, its position upstream is also critical.

Interestingly, while the response of $\Delta \mathrm{Tw}_{\mathrm{mean}}$ and $\Delta \mathrm{Tw}_{\mathrm{max}}$ to different riparian shading configurations follows broadly similar patterns to those revealed by the *AUC* and *wAUC* metrics (Fig. 8), the outlet temperature metrics ($\Delta Tw_{mean,outlet}$ and $\Delta Tw_{max,outlet}$) respond differently (Fig. 9). Our simulations indicate that while a given length of planting (eg. 2 km) at an upstream location (eg. 7.65 km) creates a relatively large temperature reduction in adjacent downstream reaches (eg. $\Delta Tw_{max} = 1.80$ °C) than the same 2 km of planting at downstream locations, this diminishes with increasing distance from the planted zone. Conversely, the same 2 km of planting located in a downstream reach (eg. 2.15 km) delivers a smaller immediate temperature reduction in adjacent reaches ($\Delta Tw_{max} = 1.31$ °C), but nonetheless maximises outlet temperature reduction ($\Delta Tw_{max,outlet}$) simply as a result of the planting zone's proximity to the basin outlet.

While these results indicate that the total planting length (ie. combination of *le* and *nz*) and location upstream (*lo*) are primary controls on stream temperature, it is important to consider the spacing between planting zones. Figs. 8 and 9 show that planting configurations comprising numerous shorter strips interspersed with spaces are associated with higher *AUC* (eg. > 148 °C km) and smaller outlet temperature reductions (eg. $\Delta Tw_{max,outlet} < 0.85$ °C) than equivalent lengths of planting that are divided into fewer strips with less frequent spaces between them (eg. 10 × 250 m strips spaced 250 m apart vs. 5 × 500 m strips spaced 250 m apart). This is particularly the case for shorter (eg. ≤ 250 m) riparian strips separated by multiple small spaces, which tend to engender small or even negligible temperature reductions even when deployed in relatively large quantities.

Stepwise linear regression fitted between *AUC* and the four planting parameters (*lo, le, nz, sp*) support these findings (Table 4). Here, the length (*le*) and number (*nz*) of planting strips (and their interaction) explained the majority of variability in *AUC*, as evidenced by the increase in model R^2 and Akaike's Information Criterion (ΔAIC) when these terms are added to the intercept-only model. This is unsurprising given that these two parameters effectively combine to equal total planting length. Planting location (*lo*) is also a strong influence (particularly in terms of ΔAIC), while spacing (*sp*) between planting zones is a relatively minor determinant of stream temperature response (less influential than the *lo:le* and *lo:nz* interactions). These results are also borne out via simple linear regression between the individual planting parameters against *AUC* (Fig. 10). This figure demonstrates that in isolation, each planting parameter can generate a wide range of stream temperature outcomes, depending on its precise value and location in relation to the other parameters, but that *lo*, *le* and particularly total planting length (*le*nz*) are primary drivers of *AUC* response.

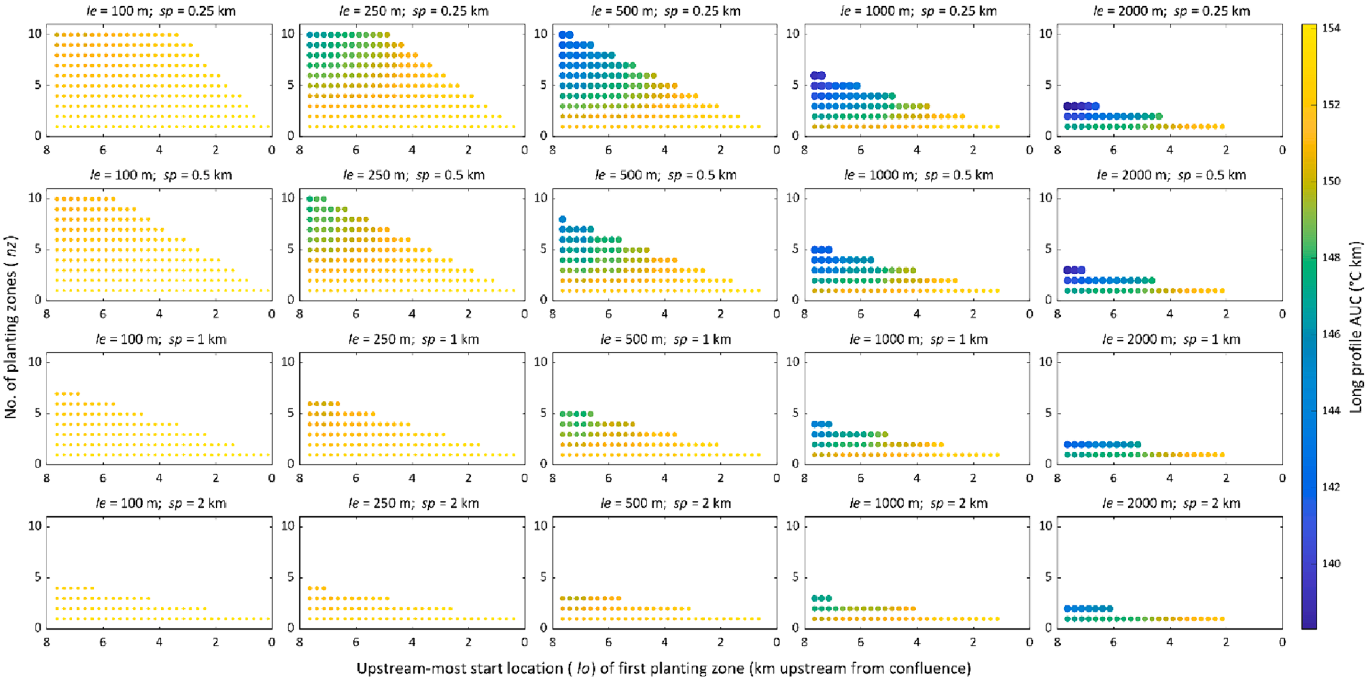


Fig. 8. Results of systematic planting optimisation scenarios showing whole-stream temperature reduction (*AUC*) as function of a given combination of length (*le*) and number (*nz*) of planting zones, spacing between zones (*sp*) and upstream starting location (*lo*) of riparian planting. Each dot summarises the Baddoch's *AUC* for a given combination of *le*, *nz*, *sp* and *lo* (eg. left-most dot on 2nd row in lower right panel ($le = 2000$ m, $sp = 2$ km) gives AUC generated by 2x 2000 m planting zones spaced 2 km apart, starting at 7.65 km upstream); lower *AUC* values indicate greater stream temperature reduction. Dot size is proportional to mean % effective shade generated by a given scenario. Figure should be interpreted from left to right. Note that scenarios with longer zones/larger spacing (and greater numbers of zones) inherently have fewer data points. Because *AUC* and *wAUC* demonstrate similar patterns when visualised in this manner, we only present *AUC* here.

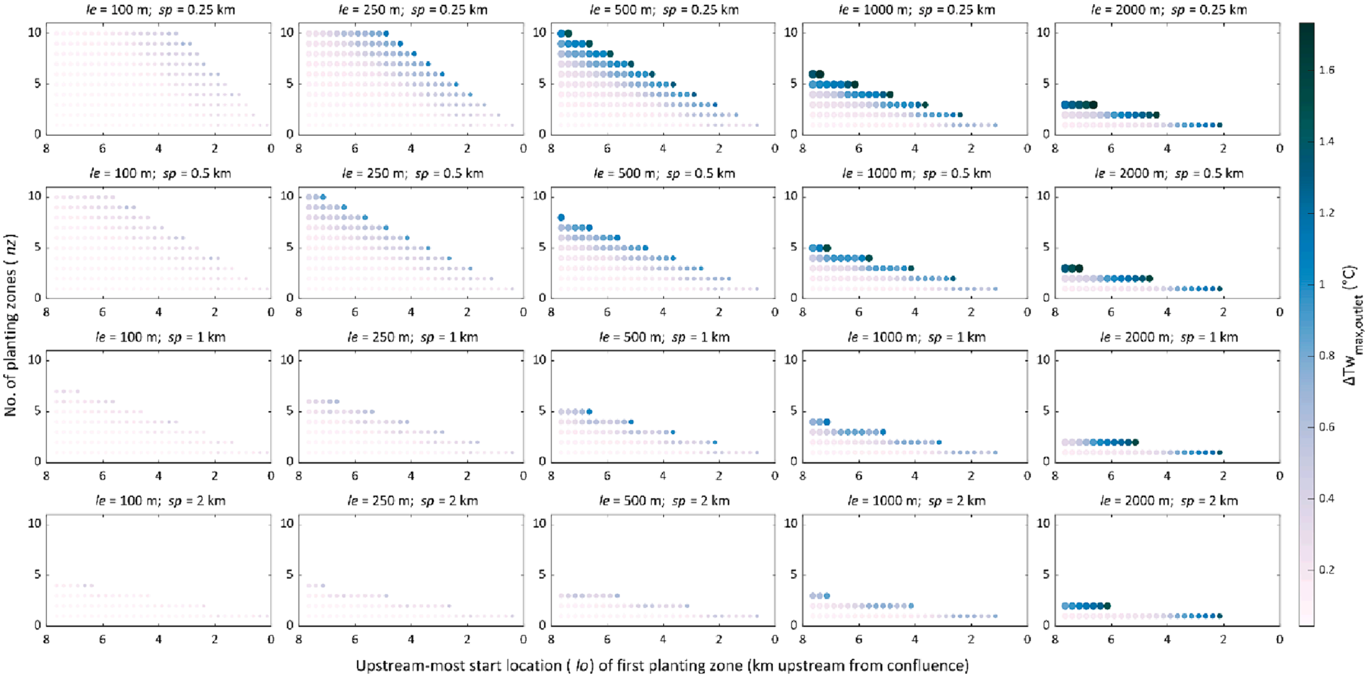


Fig. 9. Results of systematic planting optimisation scenarios showing maximum outlet temperature difference ($\Delta Tw_{max,outlet}$) as function of a given combination of length (*le*) and number (*nz*) of planting zones, spacing between zones (*sp*) and upstream starting location (*lo*) of riparian planting. Each dot summarises the Baddoch's $\Delta Tw_{max,outlet}$ for a given combination of *le*, *nz*, *sp* and *lo* (eg. left-most dot on 2nd row in lower right panel ($le = 2000$ m, $sp = 2$ km) gives $\Delta Tw_{max,outlet}$ generated by 2x 2000 m planting zones spaced 2 km apart, starting at 7.65 km upstream); higher values indicate greater stream temperature reduction. Dot size is proportional to mean % effective shade generated by a given scenario. Figure should be interpreted from left to right. Note that scenarios with longer zones/larger spacing (and greater numbers of zones) inherently have fewer data points.

Table 4
Stepwise linear regression analysis quantifying relative influence of four planting parameters (starting location [*lo*], planting length [*le*], number of planting zones [*nz*] and spacing between zones [*sp*]) on maximum temperature long profile *AUC*. Relative importance of model terms given by R^2 and change in Akaike's Information Criterion (ΔAIC) relative to final model.

Step	Terms added at step	R^2	P-value	AIC	ΔAIC
1	[intercept]	0.00	–	7985.29	–
2	*le*	0.46	<0.01	7005.52	979.77
3	*nz*	0.65	<0.01	6305.03	700.49
4	*le:nz*	0.88	<0.01	4591.39	1713.64
5	*lo*	0.93	<0.01	3639.27	952.12
6	*lo:le*	0.95	<0.01	3098.00	541.27
7	*lo:nz*	0.96	<0.01	2869.50	228.50
8	*sp*	0.97	<0.01	2630.49	239.01
9	*sp:nz*	0.97	<0.01	2520.13	110.36
10	*le:sp*	0.97	<0.01	2406.66	113.47

4. Discussion

4.1. Shade generation and stream temperature reduction under real-world riparian woodland planting

Our study is one of only a handful of investigations that simulate the stream temperature response to real-world riparian planting initiatives targeted at the creation of shading for climate change adaptation. In contrast to previous studies that focus on short reaches (eg. Hall and Selker, 2021) or simplified reach-scale modelling studies (eg. Jackson et al., 2021a), our data provide intermediate-scale (multi-reach) insights into the magnitude of stream temperature reduction that could be expected across an entire watercourse under the type of tree planting scheme that is becoming increasingly commonplace. When parameterised with data on the location and estimated height and canopy cover at maturity for recently planted riparian woodland, our simulations indicate that the Upper Dee Riparian Woodland Restoration Scheme will achieve its intended goal of reducing summer stream temperature in the salmonid-bearing lower reaches of the Burn. Simulations suggest that the tree planting is likely to achieve mean and maximum summer stream temperature reductions of 0.44 °C and 1.40 °C respectively at the Baddoch Burn's confluence compared to the current no-tree scenario.

Although the predicted temperature reductions are substantial, they are notably smaller than the 'shading effect' predicted for riparian tree cover in the Girnock Burn (mean and maximum of ~0.5 - ~1 °C and ~1.5 - ~3 °C respectively depending upon study; Dugdale et al., 2019; Fabris et al., 2018; Garner et al., 2014), another nearby tributary of the Upper Aberdeenshire Dee. This is particularly interesting given that the temperature reduction in the Girnock Burn occurs over approximately half the length of the planting in the Baddoch. A comparison of hydrometeorological data and energy fluxes associated with the present study and with previous investigations in the Girnock (eg. Dugdale et al., 2019; 2020; see supplementary materials) indicates that differences in prevailing weather patterns during the study periods are the principal reason for this disparity. In particular, mean and maximum air temperature and incoming solar radiation were much higher during the Girnock studies ($Ta_{max} = 27.1$ °C & $Ta_{mean} = 14.3$ °C; $H_{sw,\max} = 980.0$ W m^{-2} & $H_{sw,mean} = 239.9$ W m^{-2}) than in our current investigation ($Ta_{max} = 20.2$ °C & $Ta_{mean} = 11.7$ °C; $H_{sw,\max} = 728.2$ W m^{-2} & $H_{sw,mean} = 137.2$ W m^{-2}). These differences reflect a) cloudier conditions in the present investigation, b) the north–south orientation of the Girnock and its less pronounced topographic variability (meaning that it is not as affected by topographic shading as the Baddoch) and c) the higher elevation of the Baddoch. Thus, lower incoming shortwave radiation in the Baddoch Burn during our study period means that riparian vegetation could inherently not generate as large a 'shading effect' as in the Girnock Burn studies, as the stream temperature was already relatively cool. This is consistent with the findings of Garner et al. (2015), who noted that the ability of shaded reaches to offset high stream temperature is dampened when net radiation gain is lower (due to, for example, cloudy conditions).

Furthermore, while Fig. S1 indicates that tree cover in both studies attenuates solar radiation to ~20% of its unshaded value, some relatively high peak solar radiation values still occur in the Baddoch that are

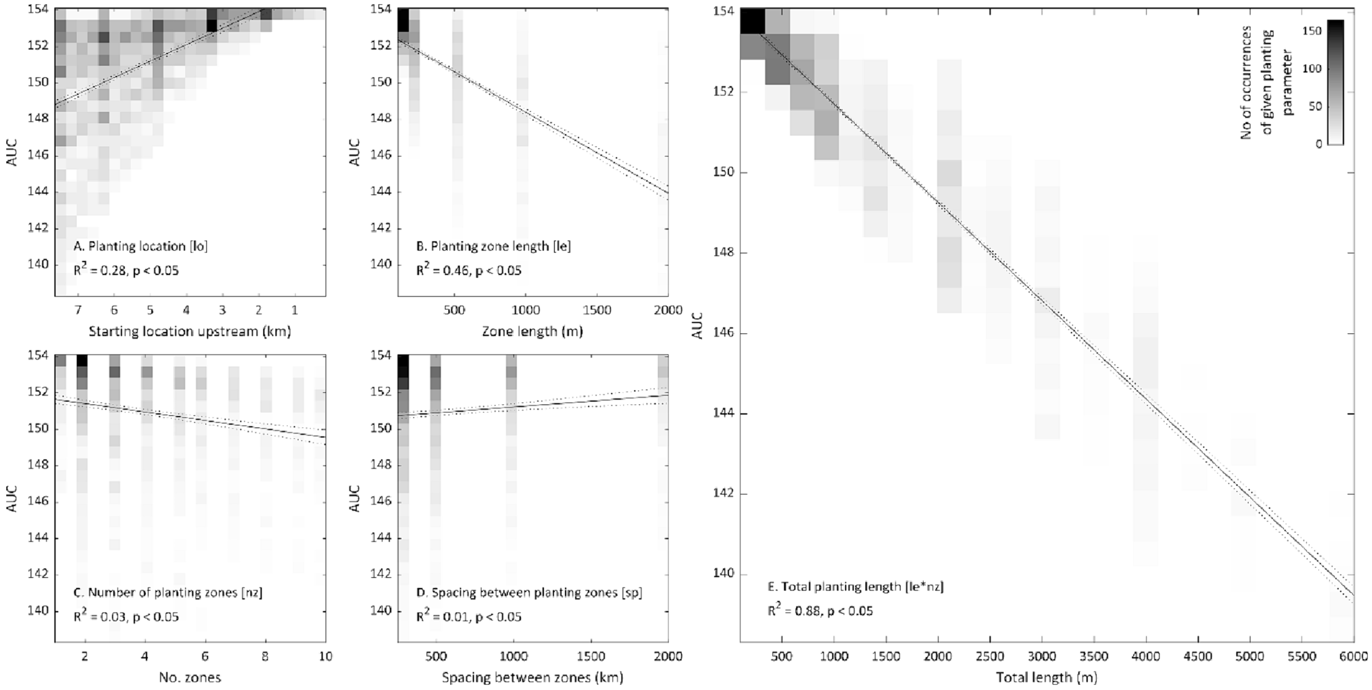


Fig. 10. Influence of individual planting parameters (and *le*nz*) on stream temperature *AUC*. Shaded cells gives the number of points of a given value of *lo/le/nz/sp/le*nz* that generate a given *AUC* response (effectively the range of variability of planting parameter values), solid line gives linear model fit with 95% confidence limits in dashes.

Table 5
General rules for riparian planting for optimal stream temperature outcomes.

Planting parameter	Stream temperature effect	Mechanism
Location upstream (*lo*)	Riparian planting in upstream reaches generally maximises the magnitude of 'shading effect' (and length of stream over which effect occurs). However, if goal is reducing stream temperature in a specific location (eg. basin outlet), then shading in adjacent reaches can in some circumstances have a notable localised effect.	Planting in upstream reaches shades stream when water volumes are low (low thermal capacity), effective shade is high due to the narrow channel and residence times are high.
Planting length (*le*)	Longer planting zones increase the 'shading effect' in comparison to shorter zones.	Longer planting zones reduce the overall radiative warming the stream experiences, helping to moderate overall stream temperature.
No. of planting zones (*nz*)	Higher numbers of planting zones increases the planting length, generating a greater 'shading effect' (see *le* above).	Higher numbers of planting zones of a given length shade more of the river channel and thus reduce radiative warming. See above.
Spacing between zones (*sp*)	Where there is a fixed planting resource, larger open areas between planting zones reduces the effectiveness of the 'shading effect'	Longer spaces between planting zones displace the (fixed) planting resource to less optimal locations further downstream where they have a lower impact. This is due to increased water volumes, lower effective shade in wider downstream reaches and shorter residence times (see *lo* above).

not observed in the Girnock. This means that simulated riparian shading in the Baddoch continues to permit moderately high solar radiation gains at certain times of day, further reducing the 'shading effect' in comparison to the Girnock. The main driver of these differences is lower effective shade in the Baddoch Burn, by virtue of its wider channel and the lack of observed data on true riparian canopy closure/overhang once woodland reaches maturity (as is already the case for the Girnock Burn). Similarly, while mean latent heat losses in the Baddoch and Girnock studies were similar (-37.0 vs −40.5 W m^{-2} respectively), the Baddoch was characterised by higher peak values than the Girnock (Fig. S1), which act to keep stream temperature lower, further reducing the simulated impact of tree shading on river temperature. While Heat Source theoretically accounts for the impact of woodland on H_e losses (via lower wind speeds/higher humidity), the physical basis by which it does so has not to our knowledge been validated and so this may represent an overestimate of true evaporative losses under tree cover. Together, these differences explain the smaller 'cooling effect' in the Baddoch simulations compared to an apparently similar neighbouring stream.

Despite the less extreme climatic conditions observed during this study, our simulations indicate that recent riparian planting within the Baddoch Burn has the potential to reduce maximum temperature on warm days and therefore increase the amount of time the river stays within thermal preferences for salmonids. Globally, our results are in line with similar studies simulating (hypothetical) responses to riparian tree planting in other locations which show a range of stream temperature responses (eg. 0.34 °C mean reduction; Abdi et al., 2019; up to 0.62 °C mean reduction; Fuller et al., 2020; 0.7 °C reduction in daily mean; Roth et al., 2010; ~1–2 °C; Trimmel et al., 2018; ~1–4 °C; Wondzell et al., 2019; 4 °C reduction in annual maximum; Sun et al., 2015). Nevertheless, the variation between these investigations again highlights the difficulty of comparing between studies that incorporate both differences in prevailing hydrometeorological conditions during the study period and inter-site differences in controlling factors (eg. discharge, stream length, etc). Setting aside these complexities, our results add to the increasing body of evidence that highlights the efficacy of riparian tree planting as a climate change adaptation measure for rising river temperatures. Our study also highlights the importance of establishing and maintaining tree cover in headwater tributaries to allow them to act as thermal refugia within their larger, and sometimes warmer, parent rivers.

4.2. General principles for prioritising riparian tree planting as a climate change adaptation measure

While our systematic planting scenarios highlight where and how further whole-stream (ie. *wAUC*) temperature reductions might be achievable in the Baddoch Burn in future via additional planting, the results of these scenarios also form the basis of generalised 'rules' that can help inform riparian tree planting strategies for other locations (Table 5). Specifically, our findings indicate that the overall length (ie. length and number of zones) and location of planting zones are the most important factors influencing stream temperature response (with the spacing between zones being of only indirect importance), and reveal the mechanisms behind spatial variability in magnitude of the 'shading effect'.

In terms of the total length of planting zones, we found that longer and/or more numerous planting zones (of a fixed size) deliver larger stream temperature reductions. This result is unsurprising; the longer a stream is under shade, the less radiative warming it will receive. Although tree cover can potentially reduce heat losses from latent and sensible heat flux (eg. Caissie, 2016; Maheu et al., 2014) and longwave radiation (Benyahya et al., 2012), inspection of our model showed that the simulated decreases in losses from turbulent and longwave heat due to tree cover are negligible in this specific case, being an order of magnitude smaller than the bulk reduction in gains from solar radiation brought about by shading.

The interaction between planting location and planting length (see section 3.3 and Table 4) indicates that the greatest reductions in stream temperature are obtained where longer planting zones are deployed in upstream reaches. Indeed, our simulations clearly indicate that planting positioned further upstream will deliver larger stream temperature reductions (in terms of *AUC/wAUC*) than similar lengths of planting further downstream, consistent with the findings of Coats and Jackson (2020) and Jackson et al. (2021a). This is because tree cover in narrow upstream reaches generates greater effective shade by covering a larger proportion of the channel width than in wider downstream areas (see Lee et al., 2012; Fuller et al., 2020). Furthermore, upstream reaches have a lower thermal capacity (lower water volume) and lower mean column velocities (higher residence time) and are thus more sensitive to changes in energy flux (Coats and Jackson, 2020; Jackson et al., 2021a) than downstream reaches. Thus, unless headwaters are already highly shaded from local topography (eg. Johnson and Wilby, 2015), planting in upstream reaches maximises the reduction in radiative warming (and thus temperature) compared to downstream locations.

Perhaps unsurprisingly, the spacing between planting zones was less influential in terms of overall stream temperature reduction. This is because adding spacing between planting zones simply moves a fixed planting resource from more effective upstream locations (where it has greater impact on stream temperature for the reasons discussed above) to less effective downstream ones, delivering sub-optimal outcomes in terms of overall temperature reduction. This is in agreement with Kail et al. (2021) who note that canopy openings should be avoided to maximise stream temperature response to riparian planting, and mirrors findings by Swartz et al. (2020) who observed that river temperature response to canopy gaps was generally small. A more detailed quantitative discussion of the mechanisms behind this phenomenon specifically in relation to the Baddoch Burn is given in the supplementary information. However, this further highlights the role of planting location and length as primary controls on the shading effect, and emphasises the importance, where logistical and practical considerations permit, of planting contiguous strips of woodland in optimal locations.

While these results indicate that riparian planting should normally target upstream reaches to maximise 'whole-river' temperature responses (in terms of *AUC* or *wAUC*), results of our $\Delta Tw_{max,outlet}$ simulations (Fig. 9) highlight a potential caveat. Here, we found that $\Delta Tw_{max,outlet}$ was maximised by applying shade in the reaches immediately upstream of the confluence (rather than in more distant upstream areas). This may ostensibly suggest that if reducing temperature at a specific location is the objective (eg. to moderate stream temperature in areas of known salmonid habitat), then locating shading in adjacent reaches can sometimes create a greater temperature response than planting located in ostensibly optimal areas (ie. headwater reaches). However, it is important to note that this effect is extremely site-specific and will be limited to smaller streams. In larger, higher order water courses, the greater width, thermal capacity and mean column velocity is such that planting has a lesser effect on stream temperature, even in adjacent reaches (Jackson et al., 2021a). Any riparian shade generation initiative targeting specific locations must therefore also be accompanied by a thorough consideration and understanding of site-specific factors affecting the feasibility and implications of tree planting (see section 4.3).

Overall, these results are consistent with those of Jackson et al. (2021a) which aimed to prioritise tree planting locations at large spatial scales. Specifically, optimal reaches for riparian planting were upstream reaches with smaller water volumes, higher potential for effective shade (ie. narrow width), and longer residence times. However, our results go beyond this reach scale prioritisation exercise to reveal the cumulative consequences of alternative planting strategies and the need to consider project objectives (eg. overall temperature reduction, versus temperature reduction at the outflow) when making tree planting recommendations.

4.3. Practical and ecological considerations of riparian tree planting

While section 4.2 provides useful information that can be used to guide riparian tree planting initiatives, it is important to consider that the real-world application raises a number of important considerations that may constrain the pursuit of optimal strategies in practise. When river temperature is the sole target of management and resources are constrained it is always better to locate planting in optimal locations, rather than distribute it more widely where the overall benefits are reduced. However, site-specific concerns will always be relevant. For example, our results indicate that additional stream temperature reductions in the Baddoch Burn may be achievable through the deployment of further long planting zones in the upstream-most reaches. In reality though, this is likely to be difficult for a variety of reasons including a) the inaccessibility of the remote upstream reaches of the Baddoch Burn, b) the acid peat bog terrain in the headwaters which may negate the successful establishment of certain tree species, c) potential for carbon loss from soils, and d) landowner desires to ensure that deer have unimpeded access across the landscape. While these considerations are specific to the current study, riparian planting in other locations (both Scotland and worldwide) are likely subject to similar considerations in relation to accessibility and land suitability.

In this vein, river managers are also likely to want to balance climate adaptation alongside the other benefits of riparian woodland including elevated organic matter inputs and enhanced nutrient retention (eg. Tolkkinen et al., 2020), increased macroinvertebrate biomass (eg. Thomas et al., 2016), and reductions in 'nuisance' periphyton (eg. Halliday et al., 2016). It is therefore advisable that planned riparian planting is carried out not just with a thorough understanding of likely stream temperature outcomes, but also with a broader appraisal of the ecological co-benefits that tree cover will likely create. Furthermore, given the increasing realisation of the importance of thermal habitat heterogeneity for aquatic ecosystems (eg. Fullerton et al., 2018; Marsha et al., 2020; Steel et al., 2017), riparian planting should be done in such a way that it promotes spatio-temporal variability in thermal (and other) habitats, rather than stifling it through the bulk application of dense commercial (coniferous) woodland that is known to reduce primary productivity (eg. Gjerløv and Richardson, 2010; Johnson and Almlöf, 2016) and salmon densities (Malcolm et al., 2019). River managers should therefore note the potential for both synergies and conflicting outcomes between river management activities with differing objectives (discussed further in Text S3 of supporting information).

Finally, our study demonstrates the importance of considering and defining appropriate metrics by which to assess the (likely) outcomes of riparian planting. We show that metrics targeting point temperature reductions (eg. ΔTw_{max}, $\Delta Tw_{max,outlet}$) are not always well-suited for assessing whole-river thermal responses to riparian shading, while other whole-river metrics (eg. *AUC*) can give insufficient consideration of ecologically-relevant information such as the wetted area over which a temperature effect occurs, or the location of important habitats (eg. areas of juvenile productivity). As such, we advocate the use of ecologically-relevant temperature metrics such as the wetted area under-the-curve (*wAUC*) demonstrated here as a means to better encapsulate the holistic impact of riparian shading across the whole stream. Nonetheless, we also acknowledge the need for research into further metrics that are capable of targeting other ecologically-important criteria, such as the relative ability of newly 'cooled' sub-catchments to act as thermal refugia *vis-à-vis* their parent rivers, as well as metrics that encapsulate/illustrate space–time variability in the uncertainty associated with model outputs. Similarly, it is important that the balance of shading across an entire catchment does not target already cool tributaries, and instead promotes planting in other locations where shading might have a greater downstream impact.

4.4. Constraints and limitations on stream temperature modelling and calibration

Despite the high degree of accuracy with which our model was able to simulate observed stream temperature (mean RMSE $\lessapprox 1\ ^\circ$C), error was not systematically distributed. While local increases (eg. 7.05 km) in RMSE likely relate to accidental placement of temperature loggers in locations prone to dewatering or the presence of un-surveyed hyporheic seepage zones, RMSE also increased monotonically as a function of distance downstream from the model's boundary condition. This error likely relates to limitations in Heat Source's process representation of 1) energy fluxes and 2) mass transfers, but may also be linked more broadly to 3) the model calibration process.

In terms of errors relating to 1) energy fluxes, our results highlight a tendency towards underprediction of river temperature at more downstream locations during all but the warmest days (Figs. 4, 5). We are confident that our simulated radiative fluxes are well constrained as these data are measured directly by weather stations located along the Baddoch Burn (Fig. 1). It is thus likely that these biases relate more to simulation of turbulent heat fluxes, which are empirically derived from other input meteorological data. Indeed, Heat Source uses a Dalton-type equation to simulate latent heat gains/losses as a function of wind speed and vapour pressure, a method known to be oversimplistic (eg. Dugdale et al., 2017) and linked to overestimation of evaporation (Ouellet et al., 2014) at certain wind speeds and humidities. As such, it is likely that its use to simulate latent heat flux accounts for the negative bias in simulated water temperature at downstream locations. However, as our investigation primarily focuses on the attenuation of the (well constrained) radiative fluxes by tree shading, we are not concerned that the bias from turbulent fluxes changes the overall conclusions of this paper; rather, the negative bias means that the 'shading effect' from recent tree planting may be of slightly greater magnitude than that highlighted in Fig. 6, ultimately reinforcing our findings and discussion in sections 4.1

and 4.2.

Errors relating to 2) mass transfers may result from a range of interrelated factors. Because Heat Source does not include a hydrological model component, it was necessary to estimate discharge from incoming tributaries in the absence of gauging data. This may have resulted in an under- or overestimation of the relative contribution of cool water from these sources. Similarly, it is also possible that some proportion of error relates to inadequate groundwater characterisation. Because the Baddoch's groundwater regime is poorly understood, we assumed constant groundwater and hyporheic inputs throughout our model. However, in reality, groundwater-surface water interactions are likely more complex. Our inability to encapsulate these groundwater inputs in the model may account for the increased RMSE in these lower reaches, and future modelling should therefore aim to incorporate spatially explicit data on hyporheic inputs and groundwater inflows where possible. Alternatively, increased RMSE in the lower reaches of the Baddoch Burn may also arise from errors associated with Heat Source's hydraulic model component. Stable solutions to the St-Venant equations used to simulate hydraulics in Heat Source are difficult to achieve under low flow conditions (eg. Saleh et al., 2013), where wide, shallow lower reaches, the high roughness height relative to water depth (see Marcus et al., 1992) and the presence of numerous emerging boulders means that simulated hydraulics may insufficiently encapsulate true flow complexity. As a result, it was it was necessary to use an abnormally high value of Manning's *n* to generate simulated velocities/depths that corresponded to our field observations. Furthermore, Heat Source's hydraulic model, which generates simplified trapezoid channel cross-sections rather than requiring true bathymetric inputs, means that water depths and velocities are subject to uncertainty. Although we did find good agreement between our simulated and observed values, detailed hydraulic surveys would be required to ensure that simulated residence times are appropriate and not responsible for the negative temperature bias noticed in the lower sections of the Baddoch Burn where the river becomes wider and shallower (potentially driving artificially high simulated heat loss). Nevertheless, despite these sources of error, RMSE was within similar limits to other studies using Heat Source (eg. Bond et al., 2015; Woltemade and Hawkins, 2016; Justice et al., 2017; Trimmel et al., 2018; Dugdale et al., 2019); given that the predicted temperature difference between the baseline and future tree planting scenarios (1.44 °C) is substantially greater than the model's RMSE and that the model is negatively (rather than positively) biased, we are confident that our model is suitable for simulating tree shading effects on high stream temperature events in the Baddoch Burn.

Error may also arise from 3) the model calibration process. Specific details on calibration of river temperature models are often unavailable or omitted in the wider literature (eg. Abdi et al., 2020b; Wanders et al., 2019, Lee et al, 2012; White et al., 2017), and by highlighting our calibration process, we hope to encourage further transparency on river temperature model calibration. In our investigation, error may have arisen from two areas of our calibration strategy. First, as our specific interest is in simulating water temperature during low flows/warm days that will become more frequent under future climate change, we deliberately chose to calibrate our model on a relatively short (ie. 1 month) period of high water temperatures, similar to other studies (eg. Abdi and Endreny, 2019; Bond et al., 2015; Dugdale et al., 2019; Garner et al., 2014; Hall and Selker, 2021; Justice et al., 2017; Woltemade and Hawkins, 2016). Although the fact that we calibrated/validated across 18 logger sites means that the number of data points involved in our multi-site calibration (eg. Rincón et al., 2023) was relatively high, we nonetheless acknowledge that this relatively short period means that we cannot be certain how our model will perform over longer periods and/or for different hydrometeorological conditions. While we cannot be sure about how future climate change will alter runoff and temperature regimes in the Baddoch Burn, in the absence of a coupled climate-hydrological model which simulates full basin hydrology as well as water temperature, we are confident that our findings are applicable to other periods with similarly warm hydrometeorological conditions and a reasonable approximation of future conditions in the Baddoch. Our decision to focus calibration on a relatively short period was primarily to avoid issues associated with optimising our model for a longer period which, given prevailing meteorological conditions at our study site, would have biased it towards reproducing cooler, wetter conditions which usually predominate, rather than the warmer low flows that are of interest. However, our focus on a period dominated by low flows also relates to practicalities linked to Heat Source's hydraulic model component. Limitations surrounding the hydraulic modelling of small streams (discussed above) means that it is difficult to obtain a hydraulic model calibration that can simulate both very high *and* low flows without prompting floating-point errors (linked to solving the St-Venant equations for very low water volumes relative to channel width/depth) or necessarily greatly increasing the simulation's spatio-temporal resolution to avoid this (with large negative consequences for model runtime). Given that our model runtime is already high (~25 min per calibration run), further extending the calibration period to include more variable hydrometeorological conditions would compound calibration runtime and be infeasible within the remit of this study. To the best of our knowledge, the Baddoch Burn is the smallest watercourse (by catchment area) on which Heat Source has been implemented, and we therefore call for the development of process-based temperature models with hydraulic components specifically suited to simulating flows in similar small, shallow upland streams that are prone to temperature extremes.

Second, we acknowledge that our relatively simple Monte Carlo optimisation approach based on Latin Hypercube sampling (rather than using a more advanced optimisation algorithm; eg. Zheng and Wang, 1996) means that a different parameter combination could potentially have achieved an improved RMSE. However, given the relatively tight range of physically-plausible values that Heat Source's parameters can take, and in light of the fact that our optimisation followed a primary manual calibration phase which narrowed down the parameter space prior to the LHC optimisation phase, we are confident that our optimised parameter set is close to the best possible and thus well-suited for accurately modelling river temperature in the Baddoch Burn. While a more advanced optimisation algorithm may have yielded slightly refined parameter values and thus marginally further improved our model's RMSE, our existing model optimisation of 10,000 parameter combinations required ~21 days to complete using parallel processing; the addition of further optimisation cycles would likely render calibration runtime infeasible. Furthermore, we believe that error in our simulations relate less to our final optimised parameter set, and more to the Heat Source's process representation (ie. turbulent fluxes) and/or our characterisation of groundwater and tributary inputs to the model. While we therefore believe that our optimisation strategy was suitable for the purposes of our investigation, we nonetheless call for further discussion of model optimisation strategies specific to calibration of river temperature models.

4.5. *Areas for future research*

While our scenarios provide useful information for river managers and practitioners looking to develop reach-scale tree planting strategies, we advocate follow-up research with a view to addressing four key knowledge gaps. First, our model focuses predominantly on the capacity of riparian shading to reduce stream temperature through reduced solar radiative flux. However, it is important to remember that riparian planting also reduces turbulent heat fluxes (ie. evaporation and convection; Dugdale et al., 2018b). While Heat Source does have routines that ostensibly simulate this effect (Boyd and Kasper, 2003), to the best of our knowledge, this has not been tested against observed data. Furthermore, the relatively simplistic manner in which Heat Source computes turbulent fluxes (see section 4.4) means that simulated latent heat fluxes even outside of tree planting zones are likely a notable contributor to model error. On this basis, future research should look to validate not only simulated reductions in latent heat flux produced by riparian tree cover, but more generally the accuracy with which simulated turbulent fluxes match observed data (using floating minipans or similar; eg. Maheu et al., 2014) with a view to assessing confidence in this energy flux parameter and thus extent to which this reduction in evaporative cooling offsets any stream temperature moderation achieved by riparian shading.

Second, as we only model a single channel, our study does not examine the combined roles of tree planting and advection in moderating stream temperature in larger downstream rivers. In reality, riparian planting initiatives often entail tree planting of several tributaries within a larger catchment; however, the water temperature response downstream of these tributaries will depend not only on the length and configuration of riparian shade within each tributary, but also on the relative contribution of each tributary and their residence times (eg. Jackson et al., 2021a). Thus, research should look to build upon this paper by testing similar tree planting scenarios across entire headwater networks with a view to understanding how the configuration of planting and discharge/velocity of each tributary interact to influence stream temperature responses in larger mainstem rivers.

Third, our research only provides information on the likely effect of tree shading at maturity, but does not consider either the length of time needed for trees to attain such a point, nor the potential for provision of partial shade by saplings during their juvenile phase. Native hardwood saplings planted in the Baddoch Burn (eg. birch, alder, willow) can attain the heights simulated in this study within 15–20 years (Price and Macdonald, 2012). Although some species (eg. rowan) take longer to grow, it is likely that a stream temperature response will nonetheless be generated by moderate-height saplings, even before tree cover reaches full maturity. Given the relative speed of forthcoming climate change impacts on rivers, it is likely that this pre-maturity phase of temperature moderation will become increasing important in offsetting stream temperature increases. Further research should therefore look to quantify how long is needed before tree planting of the type deployed in the Baddoch Burn is able to provide a useful impact on stream temperature, in relation to the onset of projected climate-driven stream temperature increases. Similarly, while Heat Source does allow for modelling of overhanging vegetation when it reaches maturity, the routines that do so are nonetheless relatively simplistic, and future work should therefore aim to incorporate advances in canopy overhang modelling (eg. Li et al., 2012; Rutherford et al., 2018, 2023) or the simulation of fractional tree shading (Abdi et al., 2020a) to ensure that this aspect of tree growth is appropriately accounted for.

Fourth and finally, while the results of this investigation provide useful guidance for riparian planting initiatives in a temperate river context, there is a clear need to better understand the response of rivers in other regions to climate change and thus develop aligned management strategies. Future research should therefore aim to understand the nature of stream temperature heterogeneity and tree cover across biomes, landscapes, and locations, with a view to developing region-specific climate change adaptation guidance.

5. Conclusions

This paper supports and expands the evidence base from which river scientists and managers can draw in order to develop improved strategies for combatting climate change-driven river temperature extremes. Our investigation not only highlights the extent to which an ongoing real-world tree planting scheme will likely deliver summer stream temperature reductions, but also synthesises general information on optimal planting configurations for delivering a temperature reduction in a desired location. While previous research has examined the temperature response to particular tree planting configurations at localised (habitat unit) extents or over larger areas (in terms of conceptual ‘planting priority’ metrics), we bridge these two domains to shed new light on how the position and amount of tree planting at the reach scale can drive substantial variability in river temperature response at locations not directly affected by shading. We show that the total length of tree planting zones and the location upstream of planting (a proxy for channel width/water volume/residence time) are the key factors driving a stream temperature response, and river managers and practitioners should therefore look to exploit these variables when developing proposals to moderate stream temperature through bankside shading. Other aspects of planting zone configuration (ie. spacing between shading zones) reduce the stream temperature response to shading by moving planting effort to sub-optimal locations; as such, contiguous zones of tree planting should be considered preferential from the point of view of delivering stream temperature reductions. Although optimising planting location and zone length will inevitably involve trade-offs relating to land access, stakeholders and other practical limitations, our results also show that even moderate amounts of tree planting, when appropriately positioned, can generate a useful stream temperature outcome. However, we stress the importance of considering not only the reach planting guidance contained herein and in studies acting at different scales (eg. Coats and Jackson, 2020; Dugdale et al., 2020; Garner et al., 2017; Jackson et al., 2021a; Kail et al., 2021; Rutherford et al., 2023), but also of consulting the literature on the broader ecological impacts of riparian planting, to ensure that the outcomes of such activities are apposite and desirable. On this basis, we advocate future studies that consider the holistic impact of tree planting across multiple spatial scales and beyond their immediate stream temperature effects, with a view to encompassing multiple criteria (eg. CO2 sequestration, pollutant filtering, natural flood management, etc) in the refinement of climate change mitigation strategies for rivers. In the context of ongoing continuous anthropogenic alterations to rivers and catchments globally, it is crucial that further deliberate interventions in river ecosystems are positive and long lasting in order to ensure the continued survival of threatened river ecosystems.

CRediT authorship contribution statement

Stephen J. Dugdale: Conceptualization, Software, Methodology, Formal analysis, Investigation, Writing – original draft, Visualization. **Iain A. Malcolm:** Conceptualization, Data curation, Methodology, Writing – review & editing. **David M. Hannah:** Conceptualization, Supervision, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgments

This work forms part of the *HoTRivers (Heterogeneity of Temperature in Rivers and Streams)* project which received funding from the European Union’s Horizon 2020 research and innovation programme under Marie Skłodowska-Curie Grant Agreement No. 702468. This research contributes to Marine Directorate Service Level Agreement FW02G, which funded IAM’s contribution to the project. We wish to thank Stephen McLaren, Denise Stirling, Pauline Proudlock and Ross Glover of the Scottish Government Marine Directorate for help with data collection in the Baddoch Burn.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jhydrol.2024.131163.

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