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Spatial distribution of thermal refuges analysed in relation to riverscape hydromorphology using airborne thermal infrared imagery

Stephen J. Dugdale [a,b,*], Normand E. Bergeron [a,b], André St-Hilaire [a]

[a] Institut National de la Recherche Scientifique, Centre Eau Terre Environnement, 490 rue de la Couronne, Québec G1K 9A9, Canada
[b] Groupe de recherche interuniversitaire en limnologie et en environnement aquatique (GRIL), Canada

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ABSTRACT

Water temperature governs the distribution and behaviour of fish. Riverine salmonids use discrete cold water patches, termed thermal refuges, when stream temperature exceeds their thermal tolerances. Currently, little is known about the mechanisms driving the spatial distribution of thermal refuges, particularly at large scales. Given the threat posed by climate warming to salmon populations in Europe and North America, thermal refuges are increasingly important for salmonids during summer. In this study, we used airborne thermal infrared (TIR) imagery to characterise the spatial distribution of thermal refuges from ~700 km of rivers in an eastern Canada salmon watershed. Thermal refuges were classified into a range of categories, and those identified as being driven by groundwater processes were observed to be both the most abundant and most spatially variable. Spatial analysis was used to assemble a range of landscape metrics that were tested for associations with the spatial distribution of groundwater-driven refuges. Associations between landscape metrics and the individual occurrence of thermal refuges were assessed using Jacobs' selectivity index. Results showed that the occurrence of groundwater thermal refuges was significantly associated with high values of channel curvature and close proximity of incoming tributary valleys (X^2 $p < 0.05$, df = 9). Regression was used to assess correlations between landscape metrics and the density of thermal refuges (number per river km). Channel confinement was found to correlate strongly with the density of groundwater thermal refuges using a quadratic model ($R^2 = 0.83$, $p < 0.05$). Our study is the first to quantify the relationship between the spatial distribution of groundwater thermal refuges and landscape hydromorphology throughout a riverscape. This information can be used to aid conservation efforts and manage critical thermal habitats in rivers and streams.

1. Introduction

Rivers are dynamic landscape features that vary substantially in both their spatial and temporal axes. River habitats are therefore diverse, comprising a mosaic of ecosystems that exist as a function of the local physical environment (Fausch, Torgersen, Baxter, & Li, 2002; Malard, Tockner, Dole-Olivier, & Ward, 2002; Stanford & Ward, 1993; Ward, 1998; Ward, Tockner, Arscott, & Claret, 2002). As with other physical habitat variables, water temperature plays an important role in governing the taxa present within a river (Armstrong, Kemp, Kennedy, Ladle, & Milner, 2003; Breau, Cunjak, & Bremset, 2007; Fausch et al., 2002; Ward, 1985), and local variations in water temperature can exert a large influence on both the type and distribution of species present (Crozier et al., 2008; Ebersole, Liss, & Frissell, 2001; Meisner, 1990; Rahel, Keleher, & Anderson, 1996). This is particularly relevant with regard to salmonid fishes, which are highly intolerant of temperature extremes (Elliott, 1991; Ficke, Myrick, & Hansen, 2007; Jonsson & Jonsson, 2009) and use variations in thermal habitat to avoid heat stress during summer (Breau et al., 2007; Ebersole et al., 2001; McCullough et al., 2009; Olden & Naiman, 2010). These thermal variations often manifest as discrete units of cold water that are cooler than the main river stem. Termed thermal refuges (Torgersen, Ebersole, & Keenan, 2012; Torgersen, Price, Li, & McIntosh, 1999), recent studies have documented their use by Atlantic salmon for thermoregulation (Breau, Cunjak, & Peake, 2011; Breau et al., 2007; Cunjak et al., 2005). In recent years, rivers in North America have increasingly experienced summer water temperatures in excess of the upper critical threshold temperature for Atlantic salmon (~23 °C; Jonsson & Jonsson, 2009; Jeong, Daigle, & St-Hilaire, 2013; Dugdale, Bergeron, & St-Hilaire, 2013; Monk, Wilbur, Curry, Gagnon, & Faux, 2013) and future climate change scenarios indicate that this trend will continue (Arnell & Reynard, 1996; Elliott & Elliott, 2010; Ficke et al., 2007; Graham & Harrod, 2009). It is therefore likely that thermal refuges will be increasingly important in ensuring the provision of cool water habitat used by salmon and other cold water fishes for the reduction of temperature-related mortalities.

Importance has previously been placed on understanding the spatial distribution of thermal refuges within the riverscape with a view to

* Corresponding author at: Institut National de la Recherche Scientifique, Centre Eau Terre Environnement, 490 rue de la Couronne, Québec G1K 9A9, Canada.
E-mail address: s.j.dugdale@gmail.com (S.J. Dugdale).

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managing thermally sensitive rivers (eg. McCullough et al., 2009; Torgersen et al., 2012; Dugdale et al., 2013; Monk et al., 2013). Given that the position and abundance of thermal refuges directly affect the accessibility of cold water to salmonids, knowledge of their spatial distribution and the processes governing it is of key concern. Earlier studies by Torgersen et al. (1999) and Ebersole et al. (2003) were the first to consider the distribution of thermal refuges in salmon rivers. However, these did not examine the processes driving thermal refuges and their spatial distributions at large scales. More recently, Monk et al. (2013) analysed the landscape variables controlling cold tributary refuges in the Cains River basin, New Brunswick. The study demonstrated a clear link between the temperature of tributary thermal refuges and a range of physical environmental variables (eg. refuge position in watershed, catchment gradient/elevation, soil type, forest type, presence of wetlands). However, given that the aim of their investigation was to model tributary temperatures (Monk et al., 2013), other types of thermal refuge were not analysed and there remains a clear lack of knowledge regarding their spatial variability and driving mechanisms.

Advances in high resolution remote sensing and geographical information systems offer a solution to this. The advent of low-cost thermal infrared imagery (eg. Dugdale et al., 2013) now means that large-scale datasets suitable for watershed-scale characterisation of thermal refuge distribution are a reality. However, while thermal infrared imagery can map the distribution of thermal refuges at watershed extents, the mechanisms driving thermal refuge distribution are more difficult to elucidate. Although the processes responsible for thermal refuges are reasonably well understood on an individual basis (see Torgersen et al. (2012) for a useful hierarchical summary of factors influencing thermal refuges), they are highly complex and interact at a range of nested scales. It is therefore extremely difficult to disentangle their influence on the spatial distribution of thermal refuges across a watershed. Nonetheless, recent developments in geographical information systems (GIS) technology coupled with increases in computing power and data storage capacity have started to allow for studies linking landscapes to river ecosystems in the spirit of the riverscape concept (eg. Carbonneau, Fonstad, Marcus, Dugdale, 2012; Fausch et al., 2002; Johnson & Host, 2010; Monk et al., 2013; Vannote, Minshall, Cummins, Sedell, & Cushing, 1980; Ward, 1998; Wiens, 2002). Through combining such GIS-derived landscape metrics with thermal infrared mapping of the riverscape, it is now possible to conduct a detailed examination of thermal refuges and of the fundamental processes driving their spatial distribution and density across an entire watershed.

This paper therefore uses high resolution airborne thermal imaging and spatial analysis of the riverscape to explore patterns and processes of thermal refuges in an entire Atlantic salmon watershed in eastern Canada. First, we produce an exhaustive inventory of thermal refuges across the watershed with a view to understanding how their distribution and density varies spatially. Second, we use GIS-derived landscape metrics to examine factors responsible for the local-scale occurrence of individual groundwater-driven thermal refuges. Emphasis was placed on groundwater-based thermal refuges because they are generally highly abundant (Dugdale et al., 2013; Ebersole et al., 2003) but relatively under-studied (McCullough et al., 2009). Third, we examine correlations between landscape metrics and the streamwise density of thermal refuges with a view to understanding mechanisms driving larger-scale refuge distribution.

2. Method

2.1. Study area

The Restigouche River watershed (Fig. 1) is located between southern Québec and northern New Brunswick in eastern Canada, draining an area of approximately 13,000 km^2 into the Baie des Chaleurs. It is bounded by the Chic-Choc Mountains to the north and the Chaleur Uplands to the south (Curry, 2002). The Restigouche River delineates part of the boundary between the two provinces, with the village of Matapédia, Québec situated at its confluence with its principal tributary, the Matapédia River at (47.971° N, 66.941° W). The New Brunswick portion of the Restigouche watershed is dominated by till-covered and exposed bedrock comprised of calcareous shale, limestone and slate (Curry, 2002; Wilson, 2006), while the Québec section, particularly the Matapédia River, comprises sandstone towards the north of the sub-basin and shale, limestone and slate towards the south (Crickmay, 1932; Lachambre & Brisebois, 1990). The watershed is relatively rugged, with the mountainous central and southern sections of the Matapédia sub-basin comprising peaks of up to 800 m and the Restigouche sub-basin commonly exceeding 500 m. Steep valleys in excess of 150 m deep dominate in a number of the constituent rivers (Curry, 2002; Michaud, 1922). Forests cover 93% of the basin, with approximately 4% of landscape urbanised. Agriculture is relatively sparse, only 1% and 2% of the catchment land use on the New Brunswick and Québec sides respectively (Curry, 2002). The Restigouche watershed supports a large population of Atlantic salmon and is world renowned for recreational fishing (Curry, 2002). Thermal refuges present within the Restigouche watershed have been observed to be used by salmonids during summer high temperature events (SJD, unpublished data).

2.2. Thermal refuge inventory

Airborne optical and thermal infrared (TIR) imagery of 25 major tributaries of the Restigouche watershed (approximately 696 km total length) was acquired during the summers of 2011 and 2012 in order to perform an inventory of thermal refuges. Imagery of one of the 2011 water courses found to contain high refuge densities (Thomas Ferguson stream) was re-acquired in 2012 to examine whether temporal changes in refuge distribution or density necessitated that data from 2011 and 2012 be examined separately. Imagery was obtained using a helicopter and custom-designed acquisition system consisting of a FLIR SC660 uncooled microbolometer TIR camera (640 × 480 pixels, NETD < 30 mK, 7.5–13 μm) and Canon EOS 550D digital SLR camera (5184 × 3456 pixels, standard RGB bands). Cameras were triggered by a MATLAB (MathWorks, 2009) program at a frequency of 0.5 Hz, yielding an image overlap generally in excess of 60% owing to the low groundspeed (~70 km h^{-1}). GPS data from a Garmin GPS76 CSx unit (3–5 m quoted accuracy, WAAS-enabled) was also logged using the MATLAB program, allowing the images to be tagged with their geographical position. The cameras and GPS antenna were installed in a Simplex Helipod II luggage pod with a 35 cm × 35 cm cutout for image acquisition, and mounted on a pan-tilt unit (Directed Perception PTU-D48) which was used to orient the cameras as close to nadir as possible. Target altitude for the acquisition flights was 300 m above ground level, yielding mean pixel resolutions of 18.7 cm and 2.6 cm respectively for the TIR and optical image datasets (corresponding to a footprint of approximately 120 m × 90 m). However, owing to the large difference in width among the surveyed rivers, it was necessary to conduct some surveys at higher altitude in order to ensure that the entire channel width was present within the image footprint. The survey parameters for each river are given in Table 1. Imagery was generally acquired between 11:00 and 16:00 to coincide with optimum solar angles and maximum water temperature. Infrared image radiance values were converted to temperatures using Planck's radiation law and corrected for atmospheric distortions in FLIR ThermaCAM Researcher Pro (FLIR, 2007) using flight altitude and meteorological data obtained from nearby stations as inputs. Image-derived temperatures were validated using a series of 32 Onset HOBO UA-002-64 temperature loggers anchored to the river bed. Radiant temperatures extracted from TIR images acquired at these locations were compared to the kinetic water temperatures recorded by the loggers, and a strong linear correlation was observed ($R^2 = 0.97$, $p < 0.05$, $n = 32$, RMSE = 0.45 °C, $y = 0.95x + 0.81$).

Owing to the large number of optical and thermal images acquired (>17,000 individual images), it was not feasible to georeference the