IDENTIFYING TEMPERATURE THRESHOLDS ASSOCIATED WITH FISH COMMUNITY CHANGES IN BRITISH COLUMBIA, CANADA, TO SUPPORT IDENTIFICATION OF TEMPERATURE SENSITIVE STREAMS

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ABSTRACT

We collected fish samples and measured physical habitat characteristics, including summer stream temperatures, at 156 sites in 50 tributary streams in two sampling areas (Upper Fraser and Thompson Rivers) in British Columbia, Canada. Additional watershed characteristics were derived from GIS coverages of watershed, hydrological and climatic variables. Maximum weekly average temperature (MWAT), computed as an index of summer thermal regime, ranged from 10 to 23 °C. High values of MWAT were associated with large, warm, low relief watersheds with a high lake influence. Measures of community similarity suggested that the fish community changed most rapidly through a lower transition zone at an MWAT of about 12 °C and an upper transition zone at an MWAT of about 19 °C. These results were confirmed using existing fisheries inventory data combined with predictions of MWAT from a landscape-scale regression model for the Thompson River watershed. For headwater sites in the Chilcotin River watershed (which drains into the middle Fraser River), the relative dominance of bull trout versus rainbow trout (based on inventory data) decreased with increasing predicted MWAT although the distinction was not as clear as for the Thompson River sites. The fish communities in these watersheds can be characterized in terms of very cold water (bull trout and some cold water species), cold water (salmonids and sculpins) and cool water (minnows and some cold water salmonids). The two transition zones (*ca* 12 and 19 °C) can be used to identify thresholds where small changes in stream temperature can be expected to lead to large changes in fish communities. Such clear, quantifiable thresholds are critical components of a management strategy designed to identify and protect vulnerable fish communities in streams where poor land use practices, alone or in combination with climatic change, can lead to changes in stream temperatures. Copyright © 2015 John Wiley & Sons, Ltd.

KEY WORDS: stream temperature; temperature sensitive streams; maximum weekly average temperature; water temperature criteria; fish community

INTRODUCTION

Changes in fish communities across habitat gradients, including temperature, are a ubiquitous feature of freshwater streams. Thermal conditions affect freshwater fish directly by influencing feeding rates, metabolism and growth, or indirectly by mediating biotic interactions such as the habitat-mediated competition observed among several fish species (Taniguchi *et al.*, 1998; De la Hoz Franco and Budy, 2005; Buisson *et al.*, 2008). Not surprisingly, fish distribution (Shuter and Post, 1990; Welsh *et al.*, 2001; Heino, 2002; Dunham *et al.*, 2003b; Perry *et al.*, 2005), abundance (Holtby, 1988) and community composition (Wehrly *et al.*, 2003; Brazner *et al.*, 2005) vary with temperature differences among streams. Such observations have led to the

classification of both species and fish communities according to their thermal preferences (e.g. Wehrly *et al.*, 2003). In western North America, headwater streams are typically dominated by cold water species such as bull trout (*Salvelinus confluentus*), which are first replaced with cool water species such as rainbow trout (*Oncorhynchus mykiss*), and then by warm water minnows and suckers (Rahel and Hubert, 1991; Parkinson and Haas, 1996) in warmer downstream reaches.

Given the strong biological influence of water temperature, variation in this habitat characteristic has been widely recognized as resulting in large natural differences in fish communities over small spatial areas (Vannote *et al.*, 1980). Water temperature varies between upstream and downstream reaches (e.g. Rahel and Hubert, 1991) and across a landscape (e.g. Wehrly *et al.*, 1998, 2007; Isaak and Hubert, 2001; Nelitz *et al.*, 2007; Buisson *et al.*, 2008; Hrachowitz *et al.*, 2010; Ruesch *et al.*, 2012). This spatial variation is driven by a variety of reach-scale factors

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including local climate, riparian vegetation, groundwater inputs, and channel and floodplain morphology and also by catchment-scale factors such as the drainage area, seasonal or annual runoff, and the fractional coverage of lakes and glaciers (Poole and Berman, 2001; Scott *et al.*, 2002; Moore, 2006; Kelleher *et al.*, 2011; Moore *et al.*, 2013).

Alterations in stream thermal regime resulting from anthropogenic stressors can be associated with changes in fish biology and ecology and have contributed to making freshwater fish one of the most threatened groups of species (Schindler, 2001). Such stressors include removal of riparian forest associated with logging (Gomi *et al.*, 2006; Holtby, 1988; Leach *et al.*, 2012), changes in runoff generation and riparian characteristics associated with urban development (Pluhowski, 1972; Klein, 1979), and changes in streamflow regime associated with withdrawals, diversions and impoundments (Hockey *et al.*, 1982; Hamblin and McAdam, 2003; Meier *et al.*, 2003). In addition, a number of studies have made projections of the effects of future climate scenarios on stream temperatures, individual fish species and fish assemblages over the coming decades (Eaton and Scheller, 1996; Mohseni *et al.*, 2003; Chu *et al.*, 2005; Buisson *et al.*, 2008; Chu *et al.*, 2008).

Despite the strong relationship between temperature and fish responses, it is difficult to predict the response of fish communities to thermal regime changes on the basis of estimates of optimal and lethal temperatures alone. Most importantly, such thresholds are typically species and life-stage dependent (Richter and Kolmes, 2005) and do not account for interactions among species. Furthermore, the negative effects of rising stream temperatures on cold water species can be exacerbated by fragmenting habitats and populations in upstream refugia (Meisner, 1990; Keleher and Rahel, 1996; Rahel *et al.*, 1996; Mohseni *et al.*, 2003), leading to constraints in dispersal among drainage basins (Grant *et al.*, 2007). Thermal community thresholds (i.e. where a large shift in fish assemblages occurs over a small temperature range) have been well defined in more complex communities in eastern North America (e.g. Lyons *et al.*, 2009); however, it is unclear whether similar thresholds exist for simpler fish communities in western and northern North America. If such thresholds do exist, it is also unclear what temperature values distinguish among fish communities and how such thresholds might vary across major drainages.

The purposes of this paper are as follows: (1) to define the relation between fish communities and water temperature within the fish assemblage in British Columbia (BC), Canada, which includes very cold to cool water habitats; (2) to provide evidence of temperature thresholds for community change; (3) to quantify community change as a function of temperature in a way that facilitates modelling the effects of future changes in thermal conditions caused by land use, water management and/or climatic change; and (4) to assess the operational utility of an empirically modelled thermal habitat index to predict species composition at unmonitored locations. To achieve these objectives, we performed analyses using data from a synoptic survey of fish communities across a gradient in stream temperature and a variety of ancillary habitat data. Although this approach allows for replication across streams and years, the relationship between temperature and fish communities is confounded by the presence of correlated environmental gradients. We explicitly considered these correlations by using a principal components analysis to document habitat characteristics that are inextricably tied to stream temperature in our data set. With this approach, we hoped to capture the effects of species interactions and population dynamics while enhancing our ability to interpret the causative role of temperature variation in driving fish community differences among streams.

As noted by Moore *et al.* (2013) and described by Reese-Hansen *et al.* (2012), this research was motivated by the need to support legislation in BC, Canada, that calls for identifying and protecting fish in 'temperature sensitive streams' (TSS) across the province. A TSS is defined as a stream where a small temperature increase would result in a large shift in fish community composition. Although the specific results and legislative context are local to BC, the general management concerns and analytical approach should be more broadly applicable to any region that supports a diversity of cold-water and cool-water aquatic habitats.

METHODS

Study area and overview

The study focused on streams located within the Fraser River catchment in the southern interior of BC, Canada, including tributaries to the Thompson River, the upper Fraser River and streams located in the Chilcotin headwater area, which drain into the west bank of the middle Fraser River. The study area encompasses a large range of environmental variation, from semi-arid grassland to montane forests to rugged mountains with glaciers. All of the streams have a snow-dominated hydrologic regime, with high flows during the spring–summer melt period and low flows during winter (Eaton and Moore, 2010).

There were two components to the study. The primary component focused on tributaries to the Thompson River and upper Fraser River, and employed fish observations and temperature measurements made in the same season. The second component focused on nominally third-order streams within the Thompson River catchment and the Chilcotin headwater area, and used fish observations from

an existing data base, combined with an index of stream thermal regime predicted from a regression model. Details of both components are provided in later sections.

We used maximum weekly average temperature (MWAT) to characterize thermal regime for the analysis of fish communities. This metric is computed as the maximum of a 7-day moving average of mean daily water temperature over the summer, which generally occurs in July or August (Moore *et al.*, 2013). Although the use of MWAT as a protective criterion has been criticized (McCullough, 2010), this metric was chosen for this study as it is highly correlated with metrics that describe both annual maximum and mean summer temperatures (Moore *et al.*, 2013). As a result, it represents both the acute periods of high temperatures that cause mortality and the chronic thermal conditions that influence growth, competition and reproductive success.

Nagpal *et al.* (2006), Sullivan *et al.* (2000) and Nelitz *et al.* (2007) found that MWAT correlated well with various aspects of the life history of salmonids (as inferred from bioenergetic modelling), whereas many studies have related fish species distributions and thermal tolerances to MWAT or related indices (e.g. Eaton *et al.*, 1995; Welsh *et al.*, 2001; Wehrly *et al.*, 2003, 2007; Ruesch *et al.*, 2012).

Primary component: collection of field data

Field data were collected from 24 tributaries of the Thompson River and 25 tributaries to the Upper Fraser River in the summers of 2003 and 2004 (Figure 1). Within each sampling area, tributaries share a common species pool because there are no permanent barriers to movement among tributaries. Therefore, we assume that the distribution of species among tributaries depends on local abiotic and biotic conditions, rather than access to the habitat. Within each sampling area, tributary streams to large mainstem rivers (Fraser, Thompson and Lower Nicola Rivers) were selected to maximize variance in factors influencing temperature (i.e. upstream lakes, icefields and groundwater inputs) and maximize similarity in physical habitat characteristics at the reach and site scale (i.e. reach gradient and stream depth). In the lower reaches of each tributary, two stream sites were then sampled for fish populations, temperatures and channel characteristics (Figure 1).

Stream temperature was recorded every 15 min near each fish sampling location using submersible temperature loggers. Temperature loggers were installed in all streams prior to 15 July in both 2003 and 2004. Stream temperature records were examined using criteria described in Moore *et al.* (2013) to ensure data quality prior to analysis. In most streams, data were recovered from both upstream and downstream temperature recorders. The MWAT associated with each stream was calculated as an average between the two
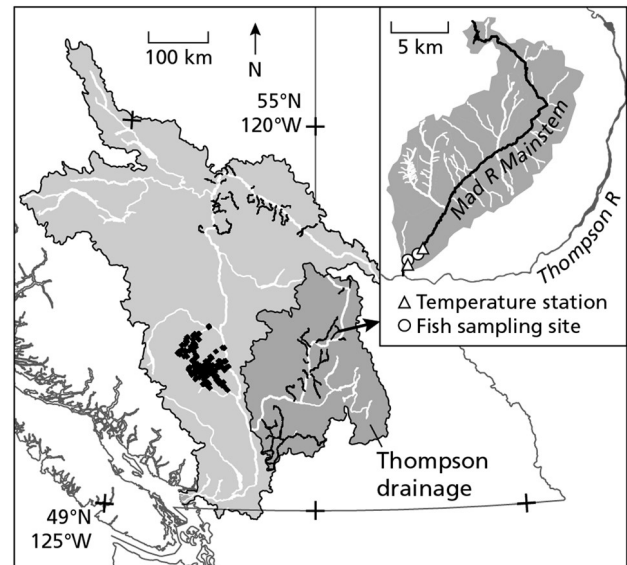

Figure 1. Study area map showing the two sampling regions and tributary streams. The inset map shows a typical watershed with the mainstem in solid black and sampling stations in a typical location near the bottom of the mainstem. The grey polygon represents the watershed area while the solid black line represents the mainstem length. The black dots indicate sampling locations in the Chilcotin headwaters area

sample locations. If only one recorder was recovered, MWAT was calculated from a single time series.

To determine relative fish abundances within each tributary, fish were sampled at two sites per tributary (upstream and downstream) between 15 July and 15 September. Fish were collected using 600 s of electroshocking effort in a single pass with a downstream stop net. Lengths, weights and species were recorded for all fish captured. We expected to observe up to 25 fish species in each sampling region (McPhail, 2007). Species found in only one tributary were designated as rare. Species represented by less than two individuals were not included in the analysis. In cases where field identification was doubtful, voucher specimens were preserved in formalin and species identification was confirmed by laboratory examination.

In addition to the determination of MWAT, each tributary was characterized using a variety of watershed and sample site variables. Many watershed variables were derived from analysis of the 1:50 000 Digital BC Watershed Atlas (BC Ministry of Environment, Lands and Parks, 1996, 2002). For a typical watershed the drainage area, mainstem, tributary streams and locations of sample sites are illustrated in Figure 1. Mainstem length, total stream length, watershed area and drainage density, as well as stream order and magnitude at the lower end of the mainstem, were derived from these types of maps. These maps were then combined with digital elevation data to derive the minimum elevation and

relief in the watershed, the gradient of the lowest 30% of the mainstem and the average gradient of terrain within the watershed. Mean July air temperature, mean annual air temperature and mean annual precipitation, as well as the proportion of total watershed area occupied by lakes, wetlands, ice and alpine tundra, were drawn from summary statistics collated in Ciruna et al. (2007). Lake influence was calculated as the proportion of total streamline length that was upstream of at least one lake within the watershed.

Site-specific information was collected at the same time as fish sampling using methods described by BC Ministry of Forests (1996). Sites were located within 1 km of the lower end of the mainstem. In all but one stream, we sampled two sites per stream. For 23 streams, we sampled both sites in 1 year, whereas for the remaining 26 streams, we sampled both sites in 2003 and 2004. Site information included measuring wetted width, bankfull width, channel depth, reach gradient and substrate size as a percent of area in four categories (>2 mm, 2–64 mm, 64–256 mm and >256 mm). Bankfull discharge was approximated by the mean annual flood, which was estimated using the regional model described in Eaton et al. (2002).

Primary component: data analysis

In field studies investigating interactions between stream temperature and biological response, the independent variable of interest (summer stream temperature) is inextricably linked to watershed characteristics that may also influence species distribution. For example, streams below lakes are typically warmer than average and those with icefields are typically colder. We also acknowledge that some species may prefer warm locations, such as lake outlets, for reasons that are independent of temperature (e.g. low sediment input). As a result, relationships between stream temperature and species occurrence derived from field data may be due to other habitat differences, rather than temperature itself.

Our approach to addressing this problem is to describe the patterns of species occurrence in relationship to a variety of correlated variables that include MWAT. These other variables are thought to influence fish distribution directly and independently of temperature (Porter et al., 2000). We used principal components analysis to express the variation among watersheds in terms of a reduced number of orthogonal dimensions relative to the original, intercorrelated variables. Given our sampling scheme, we expected some components to be loaded heavily with MWAT and correlated watershed characteristics, whereas other components would be largely independent of MWAT. Using this method, patterns of species distributions were interpreted in terms of a suite of variables associated with MWAT, rather than imputing a simple and unconfounded relationship between temperature and species occurrence.

Community structure analysis was performed by first pooling data from individual sites and streams into categories based on MWAT, with each covering an interval of 1 °C (Table IIIa and b). For each possible pairing of temperature categories, community similarity of streams was calculated using the Morisita index (I_M) (Morisita, 1959). This index takes into account relative abundance and is not affected by rare species. Consequently, it is a good measure for contrasting fish community compositions among streams with water temperature differences (Wolda, 1981). It is commonly used to compare fish assemblages spatially or temporally (Phillips and Johnston, 2004). The first step is to calculate Simpson's index of dominance (λ) separately for each thermal community j:

$$\lambda_j = \frac{\sum_{i=1}^{s} n_{ij}\left(n_{ij} - 1\right)}{N_j\left(N_j - 1\right)} \quad (1)$$

where n_{ij} represents the number of individuals of species i within thermal community j and N_j represents the total number of individuals sampled within thermal community j. Simpson's index of dominance describes the probability that two randomly selected individuals from a sample will be of the same species, where s is the total number of species in the sample. Next, the Morisita Index (I_M) was calculated for each pair of sites (j, k) using λ:

$$I_M(j,k) = \frac{2\sum_{i=1}^{s} n_{ij}n_{ik}}{\left(\lambda_j\lambda_k\right)N_jN_k} \quad (2)$$

The Morisita index ranges from 0 to 1, with 0 indicating that no species are shared between the pair and 1 indicating identical species composition.

The result from this analysis was a matrix of similarities between fish samples from each 1 °C temperature category. One dimension of this matrix represents the MWAT of the colder temperature category (i.e. reference temperature), whereas the other dimension represents a difference in MWAT between the pairs of temperature categories. For each reference temperature, we plotted similarity as a function of the difference in MWAT and then fitted either a logistic or a linear regression to these data to estimate the difference in temperature at which similarity drops to 0.5.

Secondary component: data analysis

To assess the robustness of MWAT as a tool for predicting species composition in an operational context, we used independent data to evaluate the association between MWAT and occurrences of three species. In this analysis, we used fish presence data from the Fisheries Information Summary

System, a spatially explicit database of provincial fish obser-
vations (Desrochers, 1997). We applied the empirical tem-
perature model from Moore *et al.* (2013) to estimate
MWAT for the stream locations associated with fish obser-
vations. The model is given by

$$MWAT = 7.91 + 0.484T_a + 1.18\log(A) - 0.00306Z_m$$
$$- 9.43\sqrt{f_g} + 17.5\sqrt{f_l} - 0.05296S$$
$$- 0.719k_2 + e \qquad (3)$$

where T_a is the long-term mean July–August air temperature
for the monitoring site (°C), A is catchment areas (km²), Z_m
is mean catchment elevation (m above sea level), f_g is the
fractional coverage of glaciers in the catchment, f_l is the
fractional coverage of lakes in the catchment, S is channel
gradient at the monitoring site (m/m), k_2 is an index of the
magnitude of the mean annual flood, representing the mean
annual flood (m³ s⁻¹) for a 1 km² catchment (Eaton *et al.*,
2002), and e is the prediction error. In cross-validation, pre-
diction errors (e) were approximately normally distributed,
had a standard deviation of 2.1 °C and displayed no obvious
regional patterns.

Two data sets were analysed. The first data set summa-
rized information at the third-order watershed scale. Our
analysis first extracted fish observations for bull trout (BT)
(representing very cold water species) and longnose dace
(LNC) (representing cool water species) across the entire
Thompson River drainage area. We then classified water-
shed polygons using different MWAT thresholds to define
community boundaries (i.e. separation among very cold,
cold and cool communities). For instance, we classified
polygons by varying the very cold–cold boundary from
10.5 to 15.5 °C and the cold–cool boundary from 15.5 to
21.5 °C. Next, we assessed the percentage of observations
in which either the very cold (bull trout) or cool (longnose
dace) water representative fish species were consistent with
predicted fish community type. A correct classification was
denoted when a bull trout (or longnose dace) observation
intersected with a polygon that was classified as very cold
(or cool). The temperature value at which the percentage
of correct classifications for a single species was greater
than the number of wrong classifications was used as a sur-
rogate indicator of the thermal boundary between fish
communities.

The second data set utilized species occurrence informa-
tion at individual sample points within six adjacent
watersheds that flow in different directions before indepen-
dently joining the mainstem Fraser River. These streams
(Yalakom River, Tyaughton Creek, French Bar Creek,
Lone Cabin Creek, Churn Creek and Big Creek, collec-
tively termed the Chilcotin Headwaters Area) represent an
area where bull trout (a very cold water species) and rain-
bow trout (a cold water species) coexist within each of
the six main watersheds but may be segregated at the sam-
ple point scale. These samples were collected between
1981 and 2003, and the distance between sample points av-
eraged 3 km (median = 1.1 km). Catchment characteristics
used as predictor variables in Equation 3 were determined
through GIS analysis. Mean July–August air temperature
was determined using the ClimateWNA application (Wang
et al., 2010).

RESULTS

Summary of fish sampling

A total of 5538 fish were captured in 49 tributaries (Table I,
APPENDIX A). The sampling areas overlapped with the
natural distribution of 28 freshwater fish species although
only 16 were detected in our samples. Species that were
not detected included those generally found in lakes or large
rivers as opposed to smaller streams, or those that are rare in
the sampled areas. This observation suggests our sampling
programme provided a representative sample of the fish
community. In both regions, the fish fauna were dominated
by salmonids (RB, CH, CO, BT and MW), minnows
(LNC, RSC and NSC), sculpins (CCG and CAS) and
suckers (BSU, WSU and LSU). Of the 16 species observed
across both sampling regions, CO, CRH and LDC in the Up-
per Fraser River and RSC, WSU and BB in the Thompson
River were either not observed or sample sites were out of
range from their natural distribution.

Variation in stream characteristics

Both site variables (APPENDIX B) and watershed variables
(APPENDIX C) varied substantially among tributaries.
Three principal components with eigenvalues >1.5
accounted for 67% of variation among tributaries (Table II).
Positive values represent large and warm watersheds for the
first principal component, high relief and high discharge wa-
tersheds for the second principle component, and low gradi-
ent and fine substrate sites for the third principle component.

MWAT is heavily loaded on and strongly related to the
first principal component (PC1) ($r^2 = 0.74$), but not the sec-
ond or third (PC2 and PC3) (Figure 2). Hence, for these
data, PC1 can be used to characterize variation among wa-
tersheds that is correlated with MWAT including a variety
of other watershed characteristics. As a result, associations
between fish fauna and MWAT must be interpreted as an as-
sociation with a set of correlated watershed traits rather than
MWAT alone. The Upper Fraser River sites are generally
colder than the Thompson River sites, and this difference

Table I. Species names and numbers of fish captured across the two sampled regions. *NA* indicates that the species range does not occur in the region. The list of species is derived from McPhail (2007)

Common name	Scientific Name	Species code	Sampling region Upper Fraser	Thompson	Both
Rainbow trout	Oncorhynchus mykiss	RB	692	1422	2114
Chinook salmon	Oncorhynchus tshawytscha	CH	670	236	906
Longnose dace	Rhinichthys cataractae	LNC	286	449	735
Coho salmon	Oncorhynchus kisutch	CO	*NA*	702	702
Slimy sculpin	Cottus cognatus	CCG	141	98	239
Redside shiner	Richardsonius balteatus	RSC	221	0	221
Bridgelip sucker	Catostomus columbianus	BSU	105	36	141
Northern pikeminnow	Ptychocheilus oregonensis	NSC	27	85	112
Bull trout	Salvelinus confluentus	BT	48	35	83
White sucker	Catostomus commersoni	WSU	82	*NA*	82
Prickly sculpin	Cottus asper	CAS	22	33	55
Longnose sucker	Catostomus catostomus	LSU	26	28	54
Mountain whitefish	Prosopium williamsoni	MW	18	23	41
Burbot	Lota lota	BB	27	0	27
Torrent sculpin	Cottus rhotheus	CRH	*NA*	22	22
Leopard dace	Rhinichthys falcatus	LDC	0	4	4
Pacific lamprey	Lampetra tridentate	PL	0	0	Rare
White sturgeon	Acipenser transmontanus	WSG	0	0	River
Largescale sucker	Catostomus macrocheilus	CSU	0	0	River
Mountain sucker	Catostomus platyrhynchus	MSU	*NA*	0	Rare
Lake whitefish	Coregonus clupeaformis	LW	0	0	Lake
Chiselmouth	Acrocheilus alutaceus	CMC	0	0	River
Lake chub	Couesius plumbeus	LKC	0	0	Lake
Peamouth chub	Mylocheilus caurinus	PCC	0	0	Lake
Pink salmon	Oncorhynchus gorbuscha	PK	0	0	Rare
Sockeye salmon	Oncorhynchus nerka	KOK	0	0	Lake
Lake trout	Salvelinus namaycush	LT	0	0	Lake
Pygmy whitefish	Prosopium coulteri	PW	0	0	Lake
		Total	2365	3173	5538

is reflected by the Upper Fraser River having more sites with lower MWAT and PC1 scores (Figure 3).

Species distributions

There was a considerable spread among individual species with respect to their position on the PC1 and MWAT gradients (Figure 3). Canonical correlation analysis indicates that there are differences in the overall composition of fish communities across both the MWAT and PC1 gradient ($p < 0.001$). Species that were concentrated in cooler water (BT and MW) generally had negative canonical coefficients (Table III), whereas warm water species (RSC, NSC and LNC) had positive coefficients. However, individual coefficients were not identical in the MWAT and PC1 analysis, and individual coefficients for most species were not significant when considered in isolation (Table III). This observation is not surprising because canonical correlation analysis works with linear combinations, and patterns of change between communities and temperature are probably not linear. Canonical correlations

of community composition versus PC2 and PC3 were not significant ($p = 0.432$).

Simple graphical summaries suggest that these statistical differences correspond to obvious differences in species composition across the temperature gradients in both the Thompson and Upper Fraser River drainages (Figure 4). In both regions, species found in very cold streams, such as bull trout (BT) and slimy sculpin (CCG), are replaced by cold water species such as rainbow trout (RB), whitefish (MW) and coho salmon (CO). RB, MW and CO are replaced by various cool water minnow (NSC, PM, LNC and RSC) and sucker (LSU and WSU) species at the highest temperatures. These patterns in proportional abundance generally appear to be non-linear. Some species appear to have minimum and maximum thresholds, whereas others have optimal temperatures. Although the exact pattern is not clear, BT and MW appear to have a maximum MWAT threshold, whereas LNC, RSC and NSC appear to have a minimum MWAT threshold. Although the proportion of RB and CH decline at the highest MWATs, they are still present at these values.

Table II. Results of the Principal Components Analysis (PCA) of watershed and site characteristics including means for each variable (X) and correlation with MWAT (coefficients, r; Bonferroni corrected probabilities, P). Loadings in bold are >0.5 or <−0.5. Eigenvectors and loadings for non-rotated Principal Components were derived from an analysis of the correlation matrix of watershed characteristics. One watershed (Lower Nicola) was an extreme outlier on PCA1; this data point was deleted from further consideration and a new PCA derived from the remaining 48 watersheds

Eigenvalues				Eigenvectors			Loadings		
		Correlation with MWAT		7.41	6.18	3.49			
Principal component number	Mean	r	p	1	2	3	1	2	3
Maximum weekly average temperature	15.9			0.32	−0.01	−0.09	**0.86**	−0.02	−0.17
Mainstem length (km)	38	0.66	0.00	0.28	0.21	0.01	**0.77**	0.53	0.02
Watershed area (km²)	316	0.61	0.00	0.28	0.22	−0.03	**0.75**	0.54	−0.05
Magnitude	88	0.57	0.00	0.27	0.20	0.01	**0.73**	0.49	0.01
Order	4.08	0.61	0.00	0.26	0.17	−0.02	**0.70**	0.43	−0.03
Alpine tundra (% watershed area)	4.7%	−0.58	0.00	−0.26	0.22	0.13	**−0.69**	0.55	0.24
Total stream length (km)	593	0.54	0.00	0.25	0.25	−0.02	**0.68**	**0.61**	−0.04
Watershed terrain gradient	24%	−0.58	0.00	−0.24	0.26	−0.04	**−0.67**	**0.65**	−0.07
Lake influence (% of discharge)	22%	0.50	0.01	0.24	−0.02	0.02	**0.66**	−0.04	0.04
Lakes, wetlands (% watershed area)	2.6%	0.48	0.02	0.23	−0.10	0.16	**0.61**	−0.25	0.29
Mean annual air temperature	2.43	0.55	0.00	0.22	−0.23	−0.08	**0.61**	**−0.58**	−0.16
Mean July air temperature	13.7	0.50	0.01	0.20	−0.28	−0.03	0.56	**−0.70**	−0.05
Relief (m)	1312	−0.18	1.00	−0.07	0.33	−0.17	−0.19	**0.82**	−0.32
Wetted width (site)	9.20	0.14	1.00	0.08	0.33	0.07	0.21	**0.81**	0.14
Bankful discharge (m³/s)	60	0.20	1.00	0.11	0.30	0.10	0.31	**0.74**	0.18
Bankful channel width (site)	17.9	0.30	0.93	0.12	0.30	0.05	0.34	**0.74**	0.09
Mainstem gradient (1st 30%)	2.1%	−0.35	0.37	−0.20	−0.07	−0.32	−0.54	−0.18	**−0.59**
Channel Gradient (site)	1.1%	0.16	1.00	−0.01	0.01	−0.44	−0.02	0.03	**−0.83**
Boulders >256 mm (% site area)	22%	−0.06	1.00	−0.10	0.06	−0.41	−0.26	0.15	**−0.77**
Gravel 2–64 mm (% site area)	26%	0.13	1.00	0.09	−0.13	0.39	0.24	−0.32	**0.73**
Minimum Elevation	576	−0.45	0.03	−0.17	0.03	0.30	−0.47	0.08	**0.56**
Fines <2 mm (% site area)	13%	−0.26	1.00	−0.04	−0.04	0.25	−0.11	−0.10	**0.47**
Cobble 64–256 mm (% site area)	38%	0.09	1.00	0.02	0.12	−0.23	0.06	0.29	**−0.44**
Mean annual precipitation	896	−0.37	0.28	−0.18	0.15	0.16	−0.48	0.38	0.30
Ice (% watershed area)	0.4%	−0.42	0.08	−0.17	0.20	0.14	−0.47	0.50	0.27
Maximum depth (site)	1.08	0.12	1.00	0.05	−0.07	0.10	0.13	−0.18	0.20
Drainage density (km/km²)	1.97	−0.43	0.06	−0.18	0.13	0.07	−0.50	0.32	0.13

Patterns in community similarity

The pattern of similarity (Figure 5) indicates there are two relatively sharp thresholds of community change within the temperature range represented by our sample sites. In the Thompson River tributaries, the lower threshold was between 12 and 13 °C (Figure 5c). Similarity is low when comparing the 12 °C assemblage (very cold water) to those communities in streams ≥1 °C warmer (Figure 4a). In contrast, there is high similarity when comparing the 13 °C assemblage to assemblages from streams up to 5 °C warmer, which suggests that streams in this temperature range share a similar (cold water) fish fauna. Another threshold, between 19 and 20 °C separates this cold water assemblage from a cool water assemblage found in streams with MWATs from 20 to 23 °C. Similar thresholds are apparent in the data from the Upper Fraser River (Figure 5). However, in these streams, both thresholds are at temperatures 1–2 °C colder than in the Thompson. In addition, the contrast in similarity is not as great because two common species (CH and RB) occur in similar relative abundances across a wider temperature range (Figure 4b).

Secondary analysis based on fisheries inventory information

The MWAT thresholds identified using independent fish observations and the empirical temperature model at the third-order watershed scale were consistent with those identified in the primary analysis, described earlier. In the Thompson River drainage, 60% of 158 BT observations were associated with watersheds predicted as having MWAT <12.5 °C, whereas 84% of 61 LNC observations were associated with watersheds predicted as having MWAT >19 °C.

Patterns were less clear in the Chilcotin headwaters area, where the predicted MWAT was generally lower, with no streams having MWAT >16 °C. Rainbow trout were found
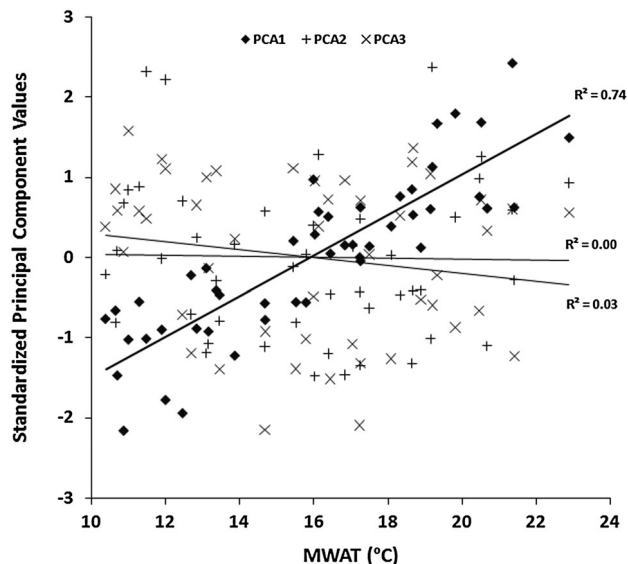
Figure 2. The relationship between stream temperature (MWAT) and the first three Principal Components derived from a matrix of 48 streams and 27 watershed characteristics

Table III. Canonical coefficients and probability of difference from zero for proportional species composition against MWAT and PC1

	MWAT		PC1	
	Coefficient	Probability	Coefficient	Probability
BT	−0.31	0.01	−0.18	0.04
RB	−0.30	0.02	−0.27	0.06
MW	−0.18	0.11	−0.18	0.13
CAS	−0.14	0.90	−0.49	0.11
CH	−0.13	0.45	0.06	0.72
LSU	−0.01	0.24	0.15	0.05
BB	0.01	0.39	0.11	0.38
BSU	0.01	0.34	0.06	0.20
CCG	0.01	0.38	−0.24	0.15
RSC	0.13	0.07	0.02	0.23
NSC	0.16	0.03	0.01	0.17
LNC	0.65	0.00	0.63	0.00

at 75% of sites and bull trout at 40% of sites, and both species were found together at only 15% of sites. Although the segregation of these two species is clearly associated with temperature (Figure 6), both species occupy a wide range of temperatures at the scale of an individual sampling site.

DISCUSSION

Previous work on the relationships between temperature and North America freshwater fish communities has
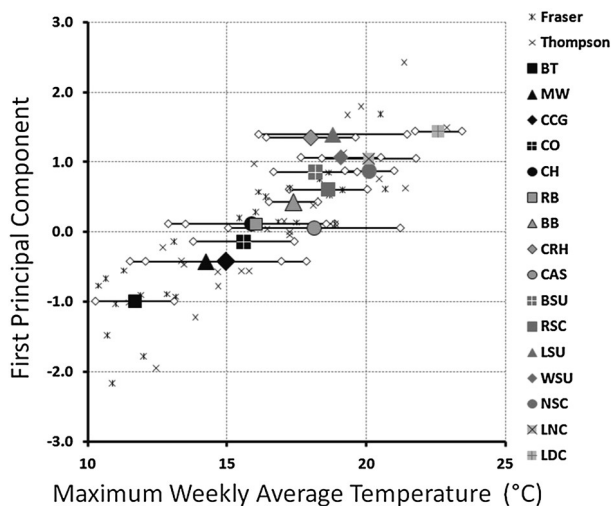

Figure 3. Sites and mean position of captured fish from each species with respect to temperature and PC1. Species codes are provided in Table I

focused on species-rich assemblages derived from the Mississippi fish fauna. The stream fish assemblage in BC has many fewer species (16) than the 99 species observed in similar-sized, more-southerly streams in Michigan and Wisconsin (Lyons *et al.*, 2009) or the 56 species per watershed in southern Ontario (Chu *et al.*, 2008). Most of this difference appears to be due to the absence of warm water species. Of 86 native freshwater species in the US Pacific Northwest listed by Zaroban *et al.* (1999), only three are classified as warm water species, and none are present in BC. In contrast, only 8 of the 99 species sampled by Lyons *et al.* (2009) were classified as cold water species. Farther north, only 15 species were observed in 196 stream reaches east of the continental divide in northern BC (Murray and Innes, 2009), and all were classified as cool or cold water by Coker *et al.* (2001).

Despite the lack of warm water species, there are two clear thresholds separating three identifiable fish communities in the BC streams studied here. Using similar methods, Wehrly *et al.* (2003) also identified two thresholds separating three thermal guilds (cold water, cool water and warm water) in the North American Great Lakes area. The BC fish assemblage appears to contain an additional guild (very cold water) that is not recognized in previous definitions of thermal guilds. BC fish communities were relatively homogeneous over several degrees Celsius, but changed rapidly across two transition zones situated at MWAT equal to 12.5 and 19 °C in the Thompson River drainage and MWAT equal to 10.5 and 18.5 °C in the Upper Fraser River. These transition zones distinguish among three temperature-linked fish communities: very cold (≤11 °C), cold (13–18 °C) and cool (≥20 °C). Single-species analyses using an independent data set identified thresholds that were consistent with these findings (12.5 and 19 °C). The cold water and cool water fish communities are analogous to the cold and cool water
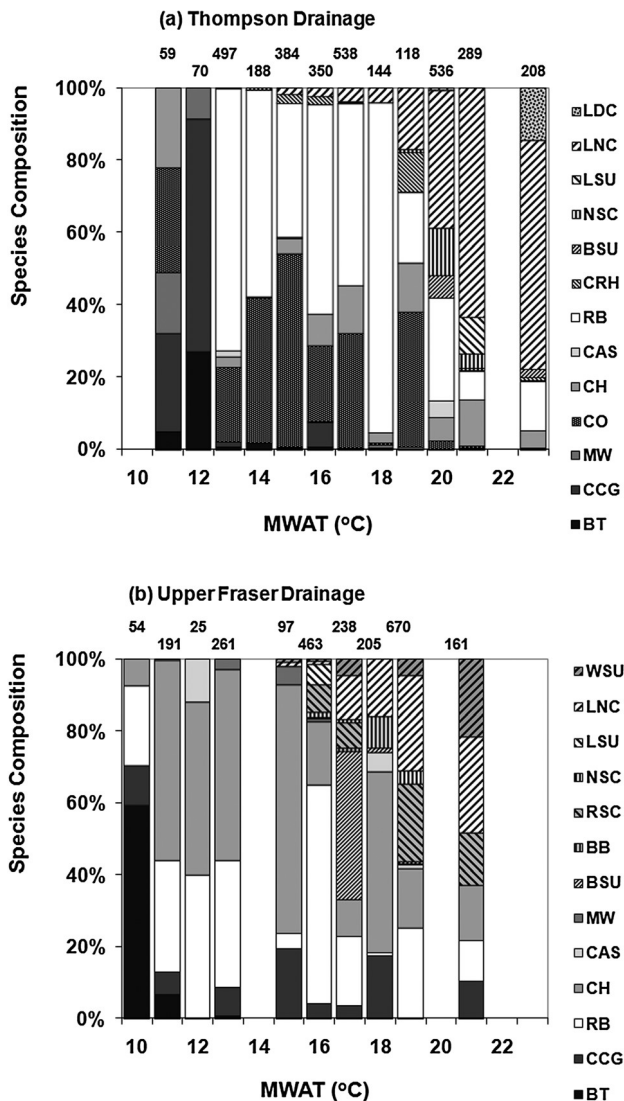
Figure 4. Patterns of species assemblages across tributaries of the (a) Thompson River and (b) Upper Fraser River drainages. Species are ordered from those which first appear at low temperatures (solid shades, bottom of legend) to those that occur only at warmer temperature (patterns, top of legend). Data from individual streams have been pooled into 1 °C temperature categories. Species codes are provided in Table I

communities described in the eastern (Eaton and Scheller, 1996; Wehrly *et al.*, 2003) and western (Zaroban *et al.*, 1999) USA.

The very cold community is defined by the presence of bull trout and in the Thompson River region by the presence of slimy sculpin, including other species found at coldwater sites. The link between very cold temperatures and bull trout distribution is well documented (Rieman *et al.*, 1997; Paul and Post, 2001; Dunham *et al.*, 2003a; Rich *et al.*, 2003), but the link is rarely discussed in the context of fish communities. Bull trout have an upper incipient lethal temperature

of 21 °C (Selong *et al.*, 2001), and their exclusion from streams >13 °C may be due to competitive interactions with other fish species such as rainbow trout (Parkinson and Haas, 1996) or in other areas with brook trout (Rodtka and Volpe, 2007). Although BT have been identified at warmer locations in BC, it is important to note that thermal specialists, such as BT, can be found at anomalous temperatures, either as a single-species population or during life stages that are less vulnerable to competition. Less is known about the thermal requirements of slimy sculpin. However, in the Thompson region, they are at the southern edge of their range in BC and are the only sculpin common in streams in Canada's northern territories ranging as far north as the Arctic Ocean (Richardson *et al.*, 2001).

The temperature threshold between very cold and cold communities was lower in the Upper Fraser than in the Thompson tributaries. At least three hypotheses could explain this difference. First, the absence of a key cold water species (CO) and higher abundances of another species (CH) in the Upper Fraser may explain this difference in threshold. Second, the Upper Fraser River and its tributaries are generally cooler than the Thompson River and its tributaries, and it is possible that physiological adaptation, combined with population level genetic differences between the two systems, could have resulted in cold-water species being able to tolerate lower temperatures in the Upper Fraser system. Eliason *et al.* (2011) documented similar processes in relation to variations in thermal tolerance among sockeye salmon populations. Third, the difference may reflect a variety of random effects that are difficult to quantify, such as simple random variation in catch composition. In addition, MWAT can vary among years by several degrees (Moore *et al.*, 2013), and the abundance of anadromous species can vary dramatically on a variety of time scales (Beamish *et al.*, 1999). Thus, the difference could simply reflect the conditions prevalent in the seasons in which sampling was conducted.

Our results, combined with a general knowledge of northern fish fauna, suggest that a guild of very coldwater species might be present in other streams across northern Canada. Candidate species that may characterize very cold water communities in other northern areas include species that are common in northern streams but are rare or absent farther south (e.g. *Lampetra alaskensis*, *Lampetra camtschatica*, *Salvelinus alpines*, *Stenodus leucichthys* and *Thymallus arcticus*). In northeastern BC, Murray and Innes (2009) used four thermal categories to classify fish communities. There are some inconsistencies between their conclusions and our results (e.g. they reported MW, RB and BT in the coldest streams). A review of the thermal preferences of Canadian fish did not reveal an additional thermal guild. Coldwater specialists such as arctic char (*Salvelinus alpines*) and BT are classified into the coldwater guild along with many of
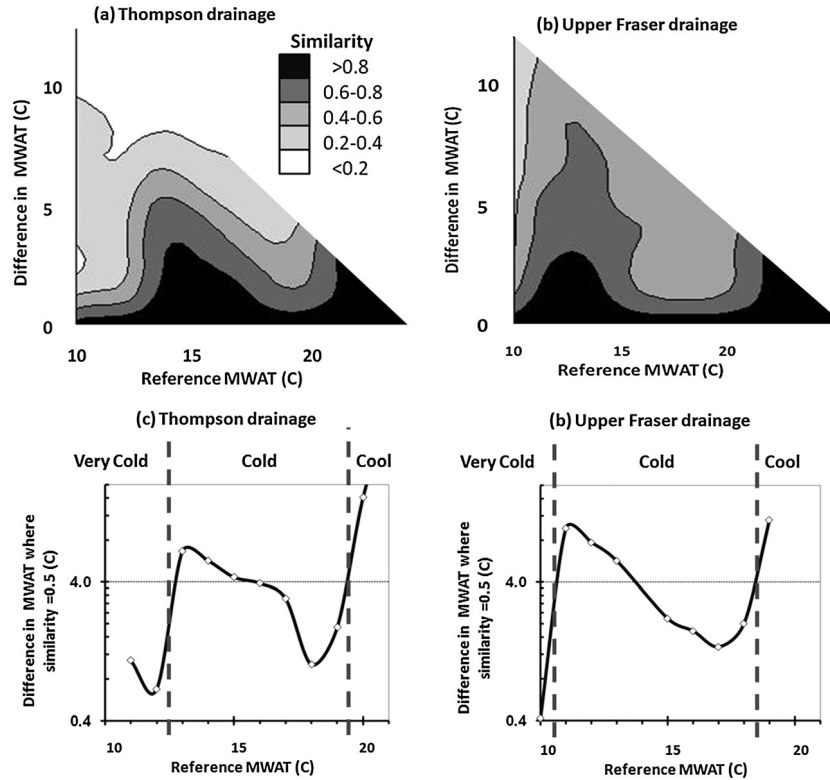
Figure 5. Contour plots of the pattern in similarity in fish species composition when comparing pairs of 1 °C temperature categories as a function of the temperature of the colder category and difference in temperature between each pair (upper two panels). Similarity values used to define the temperature ranges for very cold, cold and cool water fish assemblages in the Thompson and Upper Fraser River drainages (lower two panels). Community boundaries indicate reference values of MWAT where the temperature increase required to produce a 50% decline in similarity changes from very low (<1 °C) to high (>4 °C)

the species from southern BC (Coker *et al.*, 2001). Prompt clarification of the existence and status of very coldwater fish communities in the Canadian north is important because
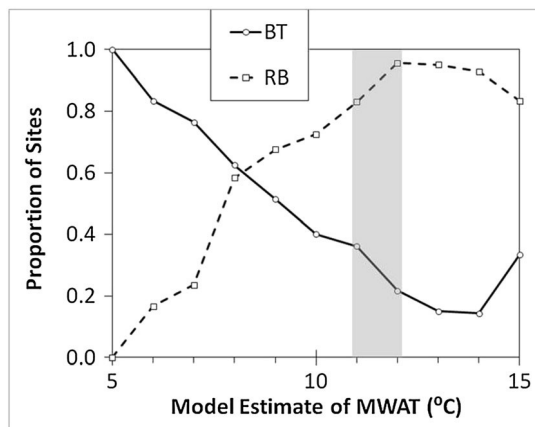
Figure 6. Presence of bull trout and rainbow trout versus MWAT at sample sites in the Chilcotin Headwaters Area. MWAT was calculated using the characteristics of the watershed upstream of each sample point using Equation 3, derived by Moore *et al.* (2013). The vertical grey band is the proposed boundary between the Very Cold and Cold water fish communities

of the accelerating pace of development and the anticipated severity of climate warming in these areas (Kaplan and New, 2006).

If present, the very cold community will likely be characterized by few species relative to the number of species in other thermal guilds. Lyons *et al.* (2009) used 32 indicator species to distinguish among four guilds—one cold water, two cool water and one warm water category. Low species numbers are characteristic of most watersheds in northern and central Canada (Chu *et al.*, 2003). Defining a 'guild' on the basis of one or two species may seem problematic. However, at least some of these contrasts will involve species that either dominate the biomass or play a keystone role (e.g. top predator), in these communities.

The absence of a warm water fish fauna in southern BC may be due to limitations in dispersal, as well as a lack of suitable warm water habitat. The BC fish fauna is less diverse than more southern and eastern areas, probably because of the history of recolonization following glaciation (McPhail, 2007). Only 6 of 57 species listed by Eaton and Scheller (1996) and 14 of 132 species listed by Zaroban *et al.* (1999) are among the 15 species found in our sampling sites. Most of the alien species in the Pacific Northwest are

classified as warm water (Zaroban *et al.*, 1999), suggesting that BC fish communities may be vulnerable to invasion by warm water exotics despite an apparent lack of warm water sites (e.g. >22 °C as indicated by Wehrley *et al.*, 2003) in our sampling area.

Our results show that temperature is correlated with some watershed-scale and reach-scale characteristics, which complicates the interpretation of a cause and effect linkage between temperature and fish community composition. MWAT was correlated with the habitat PC1 but not PC2 and PC3, suggesting that the cause of the relationship between temperature and fish community is not due to habitat characteristics that load heavily on PC2 and PC3. The variables loading onto PC1 indicate that warmer streams drained larger, lower relief basins and tended to have more lakes and wetlands. Both measures of air temperature were positively correlated with MWAT along with the presence of lakes and all five measures of watershed size. Two measures of watershed relief had negative coefficients. These relationships are generally consistent with the variables that Moore *et al.* (2013) found to be significant predictors of MWAT (i.e. those in Equation 3).

Our conclusions concerning the role of temperature as a causative agent of fish community change must be tempered by the presence of these and possibly other patterns of environmental covariation. The correlation with the presence of lakes and wetlands is the most difficult to ignore because lakes clearly have downstream effects on factors such as sediment load and flow variation, which have been shown to influence fish survival. Channel characteristics such as water depth and velocity are known to affect species occurrence and diversity (e.g. Young, 2001) and are commonly used to characterize habitat preferences of freshwater fish species. Interestingly, the lack of an association between channel characteristics and MWAT indicates that the association of fish community with MWAT in our samples is unlikely to be due to a spurious correlation with these factors.

Our inability to isolate the effects of temperature on fish communities in a synoptic survey is not unique. Experimental manipulation is sometimes perceived as a better method of defining temperature thresholds because it addresses the difficulty of inferring cause and effect from correlation studies. Whole watershed manipulations have been used to document the response of fish communities to changes in stream temperature (e.g. Holtby, 1988). However, these studies suffer from low replication and can be difficult to interpret because the effects of temperature change are typically accompanied by changes in other stream properties brought on by the manipulation (e.g. changes in streamflow and sediment concentrations). Synoptic surveys of fish communities (combined with laboratory information on temperature tolerance) will likely

remain the method of choice for defining thermal guilds (e.g. Lyons *et al.*, 2009) despite the presence of correlated and confounding variables.

The secondary component of the study suggests that the empirical model derived by Moore *et al.* (2013) has utility for predicting fish species composition at unmonitored locations and therefore has potential for use as an operational decision support tool within a risk-based framework (Nelitz *et al.*, 2008). However, the shift in species dominance from bull trout at lower MWAT to rainbow trout at higher MWAT in the Chilcotin Headwaters area was more gradual than was the case for the Thompson and Upper Fraser sites. This lack of a clear threshold likely reflects, in part, the effects of predictive uncertainty associated with Equation 3. However, the lack of a clear threshold could also be associated with the fact that the collection sites for the Chilcotin Headwaters area were dispersed along the mainstem and tributaries within each of the six main watersheds, sometimes within a few hundred metres of each other, often within the same year. In the absence of barriers to movement, the within-watershed samples are therefore not likely to be demographically independent. As a result, the presence of a species at a particular site can be affected by the characteristics of the much larger watershed downstream of the sample point as well as the characteristics of the watershed upstream. In contrast, the streams in the Thompson/Upper Fraser data set were each sampled in the lowest reach, just above the confluence with a much larger river, and are therefore likely to represent demographically independent populations.

The aforementioned results and delineation of thermal boundaries are informative for managers tasked with identifying and protecting fish communities vulnerable to stream warming as a result of land use, water use and climate change. If TSSs are legally defined as streams where a small temperature increase will result in a large shift in fish community composition, our results indicate that three conditions would need to be met to fit this definition. Sensitive streams will be as follows: (1) have current temperatures at or just below one of the fish community transition zones; (2) support species that are susceptible to replacement by warmer communities; and (3) have no physical barriers to colonization by replacement species. These conditions can be viewed as a set of filters that can form an iterative process to identify TSSs. The first filter would identify streams where current temperatures are at or just below the temperature of the transition zones predicted using a model that estimates temperature from watershed characteristics (e.g. Moore *et al.*, 2013). The second filter would then confirm the presence of a sensitive species (e.g. bull trout in the lower transition zone and any salmonid species in the upper zone). These filters would make help to focus TSS protection on the most vulnerable streams.

In this study, we used a regression model based on data collected throughout BC. In moving forward with

approaches for identifying thermal habitat conditions at unmonitored sites, we recommend that regional monitoring networks be set up to develop models that could be more specific to the geographic conditions within a given region. In particular, at the regional scale, it is more feasible to apply emerging statistical techniques that can account for spatial autocorrelation that is conditioned by the stream network (e.g. Isaak *et al.*, 2014; Peterson and Ver Hoef, 2014).

CONCLUSIONS

This study quantified the association between reach-scale thermal regime and fish species assemblages in the watersheds of the Fraser and Thompson rivers in BC, Canada. One approach involved the use of data from a synoptic-scale fish sampling conducted over 2 years. Another approach employed data from an existing fisheries inventory, combined with an index of stream thermal regime computed from a landscape-scale regression model. Measures of community similarity suggested that the fish community changed most rapidly through a lower transition zone at an MWAT of about 12 °C and an upper transition zone at an MWAT of about 19 °C. The fish communities in these streams can therefore be characterized in terms of a very cold (bull trout and some cold water species), cold water (salmonids, sculpins) and cool water (minnows and some cold water salmonids). The two transition zones can be used to identify thresholds where small changes in stream temperature can be expected to lead to large changes in fish communities. Clear, quantifiable thresholds are critical components of a management strategy designed to identify and protect vulnerable fish communities in streams where poor land use practices, alone or in combination with climatic change, can lead to changes in stream temperatures.

ACKNOWLEDGEMENTS

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APPENDIX A

MWAT AND THE NUMBER OF FISH OF EACH SPECIES CAPTURED IN EACH SAMPLED STREAM

Gazetted name	MWAT	BT	MW	CCG	CO	CH	RB	BB	CRH	CAS	BSU	RSC	LSU	WSU	NSC	LNC	LDC
Hungary Cr.	10.4	32	0	6	0	4	12	0	0	0	0	0	0	0	0	0	0
Driscoll Cr.	10.6	0	0	12	0	21	22	0	0	0	0	0	0	0	0	0	0
Mcintosh Cr.	10.7	0	0	0	0	0	5	0	0	0	0	0	0	0	0	0	0
Clyde Cr.	10.9	0	0	0	0	0	11	0	0	0	0	0	0	0	0	0	0
Ptarmigan Cr.	11.0	0	0	0	0	0	19	0	0	1	0	0	0	0	0	0	0
Dome Cr.	11.3	13	0	0	0	85	2	0	0	0	0	0	0	0	0	0	0
Snowshoe Cr.	11.9	0	0	0	0	0	10	0	0	0	0	0	0	0	0	0	0
Mckale R.	12.0	0	0	0	0	12	0	0	0	3	0	0	0	0	0	0	0
Humbug Cr.	12.8	0	1	10	0	75	18	0	0	0	0	0	0	0	0	0	0
La Pierre Cr.	13.1	0	0	0	0	0	64	0	0	0	0	0	0	0	0	0	0
Pritchard Cr.	13.2	2	7	11	0	63	10	0	0	0	0	0	0	0	0	0	0
Kenneth Cr.	15.4	0	5	19	0	67	4	0	0	0	0	0	0	1	0	1	0
Tay Cr.	16.0	0	1	16	0	31	43	6	0	0	1	36	26	0	0	3	0
Slim Cr.	16.1	0	3	4	0	50	9	1	0	0	0	0	0	0	0	1	0
Tako Cr.	16.4	0	0	0	0	0	229	0	0	0	0	0	0	3	0	0	0
Hospital Cr.	16.8	0	0	9	0	0	15	0	0	0	0	0	0	11	0	4	0
Wright Cr.	17.3	0	0	0	0	24	31	2	0	0	98	17	0	0	2	25	0
Averil Cr.	17.5	0	0	10	0	99	2	9	0	11	2	0	0	0	0	21	0
Wansa Cr.	18.3	0	0	26	0	4	0	9	0	0	0	0	0	0	0	12	0
Tabor Cr.	18.7	0	1	0	0	51	139	0	0	1	4	25	0	28	12	65	0
Olsson Cr.	18.7	1	0	1	0	24	0	0	0	3	0	0	0	4	0	10	0
Stone Cr.	18.9	0	0	0	0	35	0	0	0	3	0	0	0	0	11	3	0
Cale Cr.	19.1	0	0	0	0	0	29	0	0	0	0	120	0	0	2	98	0
Naver Cr.	20.5	0	0	3	0	25	2	0	0	0	0	3	0	34	0	43	0
RedRock Cr.	20.7	0	0	14	0	0	16	0	0	0	0	20	0	1	0	0	0
Albreda R.	11.5	3	10	16	17	13	0	0	0	0	0	0	0	0	0	0	0
Canvas Cr.	12.5	19	6	45	0	0	0	0	0	0	0	0	0	0	0	0	0
Fishtrap Cr.	12.7	4	0	0	0	0	168	0	0	0	0	0	0	0	0	0	0
Maka Cr.	13.4	0	0	6	105	13	22	0	1	0	0	0	0	0	0	0	0
Fadear Cr.	13.5	1	0	0	0	1	176	0	0	0	0	0	0	0	0	0	0
Juliet Cr.	13.9	4	0	0	0	0	20	0	0	3	0	0	0	0	0	0	0
Darlington Cr.	14.7	0	1	0	179	16	141	0	0	0	0	0	0	0	0	0	0
Harper Cr.	14.7	1	0	1	26	0	2	0	9	1	0	0	0	0	0	7	0
Nuaitch Cr.	15.5	0	0	0	79	42	174	0	1	0	0	0	0	0	0	0	0
Otter Cr.	15.8	2	0	24	19	6	37	0	0	0	0	0	0	0	0	0	0
Lemieux Cr.	16.0	0	1	0	51	22	101	0	8	0	0	0	0	0	0	8	0
Jamieson Cr.	16.5	1	0	0	3	2	64	0	0	1	0	0	0	0	0	0	0
Mann Cr.	17.1	0	0	4	163	29	78	0	2	0	0	0	0	0	0	12	0
Skuhun Cr.	17.2	0	0	0	0	0	188	0	0	0	0	0	0	0	0	0	0
Mad R.	17.3	0	0	0	1	1	30	0	0	0	0	0	0	0	0	9	0
Louis Cr.	18.1	0	1	1	1	4	17	0	0	0	0	0	0	0	0	6	0
Raft R.	19.2	0	1	0	42	4	17	0	0	0	0	0	0	0	0	12	0
Barriere R.	19.3	0	0	0	2	12	6	0	13	0	0	0	0	0	1	8	0
Guichon Cr.	19.8	0	2	0	1	25	56	0	0	0	24	0	0	0	0	53	1
Spius Cr.	20.5	0	0	0	12	11	103	0	0	0	12	0	0	0	73	160	3
Unicola R.	21.4	0	1	1	0	29	16	0	2	0	0	0	28	0	11	83	0
Tranquille R.	21.4	0	0	0	1	6	6	0	0	14	0	0	0	0	0	91	0
Coldwater R.	22.9	0	0	0	1	4	25	0	0	0	5	2	0	0	0	91	30
L. Nicola River	23.4	0	0	0	0	6	3	0	2	0	0	1	0	0	0	38	0
Total		83	41	239	703	916	2142	27	38	41	146	224	54	82	112	864	34
Average MWAT of Species (°C)		11.8	14.2	15.0	15.6	15.9	16.0	17.4	17.4	18.1	18.2	18.7	18.8	19.1	20.1	20.2	22.6

APPENDIX B

SITE CHARACTERISTICS FOR EACH SAMPLED TRIBUTARY

Sampling area	Gazetted name	No. of Sites	Wetted width (m)	Channel gradient (%)	Bankful channel width (m)	Maximum depth (m)	Fines <2 mm (% site area)	Gravel 2–64 mm (% site area)	Cobble 64–256 mm (% site area)	Boulders >256 mm (% site area)	Bankful discharge (m³/s)
Fraser	Hungary Cr.	4	10.15	2.3	15.9	0.75	3	40	40	18	55
Fraser	Driscoll Cr.	4	6.95	1.1	9.23	0.4	43	34	21	3	40
Fraser	Mcintosh Cr.	2	6.23	2.5	7.5	0.55	13	38	38	13	32
Fraser	Clyde Cr.	1	5.79	4.5	8.53	0.65	5	12	40	37	23
Fraser	Ptarmigan Cr.	2	11.75	0.3	18.17	1.1	30	68	3	5	73
Fraser	Dome Cr.	4	18.15	1.0	23.45	0.47	4	32	50	15	101
Fraser	Snowshoe Cr.	2	9.4	0.8	10.95	0.59	70	12	13	5	48
Fraser	Mckale R.	2	12.23	0.8	31.53	0.53	8	22	60	10	88
Fraser	Humbug Cr.	4	8.48	0.3	16.05	0.53	15	38	40	8	53
Fraser	La Pierre Cr.	2	4.4	3.7	7.05	0.76	18	58	19	7	28
Fraser	Pritchard Cr.	2	2.4	0.0	3.5	0.7	10	60	30	0	14
Fraser	Kenneth Cr.	4	12.35	1.3	16.6	1.16	23	60	13	5	112
Fraser	Tay Cr.	4	3.62	1.6	5.12	0.5	9	68	18	6	29
Fraser	Slim Cr.	4	19.5	0.6	34.35	0.6	7	18	48	20	164
Fraser	Tako Cr.	4	2.58	1.8	10.18	0.68	23	50	20	8	25
Fraser	Hospital Cr.	2	3.6	0.0	5.4	0.88	15	70	15	0	25
Fraser	Wright Cr.	4	4.98	0.8	7.25	0.6	17	45	38	1	42
Fraser	Averil Cr.	4	7.32	1.7	14.36	0.47	5	8	73	18	32
Fraser	Wansa Cr.	2	8.8	0.0	8.8	0.81	8	40	50	5	89
Fraser	Tabor Cr.	4	4.05	0.9	6.34	2.26	18	58	22	3	42
Fraser	Olsson Cr.	4	12.34	0.7	24.25	1.4	15	78	8	0	94
Fraser	Stone Cr.	2	8.35	0.0	18.55	0.47	5	28	30	40	44
Fraser	Cale Cr.	4	5.31	0.2	7.36	0.52	23	70	7	1	50
Fraser	Naver Cr.	4	19.05	0.7	79.1	0.4	9	49	35	7	117
Fraser	RedRock Cr.	2	4.65	0.0	8.3	0.48	8	42	50	0	33
Thompson	Albreda R.	2	21.9	2.0	29.4	0.5	22	11	67	0	133
Thompson	Canvas Cr.	4	10.35	1.0	23.15	0.45	1	67	32	0	39
Thompson	Fishtrap Cr.	2	5.95	2.5	6.67	0.69	23	18	59	0	13
Thompson	Maka Cr.	2	6.65	1.0	15.99	0.83	82	0	18	0	49
Thompson	Fadear Cr.	2	3.51	2.6	5.82	0.5	6	63	31	0	19
Thompson	Juliet Cr.	2	6.8	1.2	15.95	0.89	4	46	50	0	30
Thompson	Darlington Cr.	4	3.4	3.5	7.7	0.62	1	71	28	0	18
Thompson	Harper Cr.	4	10.45	3.0	15.9	1.38	4	78	18	0	58
Thompson	Nuaitch Cr.	4	3.5	2.5	5.8	0.26	5	11	84	0	17
Thompson	Otter Cr.	2	7.8	2.7	29.09	0.46	10	50	40	0	64
Thompson	Lemieux Cr.	4	9.9	0.6	29.05	0.72	1	29	70	0	96
Thompson	Jamieson Cr.	2	6.75	2.5	10.92	0.85	0	33	67	0	9
Thompson	Mann Cr.	4	3.5	2.0	15.85	0.26	5	43	52	0	87
Thompson	Skuhun Cr.	4	3.95	4.5	7.2	0.33	4	75	21	0	15
Thompson	Mad R.	2	12.8	5.3	17.4	1.16	6	72	22	0	99
Thompson	Louis Cr.	4	8.7	0.9	12.45	0.34	1	54	46	0	43
Thompson	Raft R.	4	32.05	2.0	42.4	0.34	3	41	56	0	226
Thompson	Barriere R.	2	21.68	0.5	45.8	2.1	31	31	39	0	168
Thompson	Guichon Cr.	4	4.25	1.5	10.78	0.4	2	6	93	0	24
Thompson	Spius Cr.	4	11.2	2.0	43.35	0.61	12	13	76	0	106
Thompson	Unicola R.	4	6.4	1.1	20.15	0.56	4	1	13	82	40
Thompson	Tranquille R.	2	7.31	2.0	11.55	0.48	14	29	57	0	13
Thompson	Coldwater R.	2	22.75	1.0	37.85	0.63	7	5	20	68	106

APPENDIX C

WATERSHED CHARACTERISTICS FOR EACH SAMPLED TRIBUTARY

Gazetted name	Area (km²)	Order	Magnitude	Mainstem Length (km)	Mainstem Gradient (%)	Min. elev. (m)	Relief (m)	Terrain slope (%)	Total stream length (km)	Stream density (km / km²)	Mean annual precip. (mm)	Lake influence (%)	Lakes	Ice	Alpine	Ann. (°C)	July (°C)
Hungary Cr.	96	3	29	25	1.6	626	1262	27	153	1.6	1062	2	0.7	0.0	4.8	2.0	13.1
Driscoll Cr.	57	3	18	16	1.5	625	1090	28	113	2.0	899	0	2.0	0.0	0.0	2.8	14.2
Mcintosh Cr.	61	3	15	13	3.6	708	1737	33	142	2.3	972	3	1.3	1.9	17.0	1.4	12.7
Clyde Cr.	39	3	19	14	5.2	705	1702	45	122	3.2	1134	0	0.0	1.2	28.9	0.5	11.4
Ptarmigan Cr.	187	4	39	42	0.7	634	1823	39	587	3.1	1103	3	1.7	1.7	18.4	1.3	12.2
Dome Cr.	278	4	67	34	0.7	631	1650	36	631	2.3	1129	5	1.6	0.4	11.2	1.7	12.8
Snowshoe Cr.	108	3	22	26	1.4	642	1834	30	269	2.5	967	14	4.3	1.1	10.3	1.9	13.1
Mckale R.	284	4	91	34	2.4	701	1766	48	1013	3.6	1371	1	0.1	6.1	31.7	0.1	11.1
Humbug Cr.	99	4	27	27	1.7	634	1473	39	260	2.6	1284	2	1.2	0.0	11.2	1.8	13.1
La Pierre Cr.	66	4	20	17	1.6	722	484	11	117	1.8	749	20	3.3	0.0	0.0	2.7	14.1
Pritchard Cr.	11	3	8	8	5.7	611	1063	23	21	2.0	1024	0	0.0	0.0	0.0	2.5	14.0
Kenneth Cr.	274	4	84	43	0.3	622	1258	21	459	1.7	900	0	3.2	0.0	1.8	2.5	13.9
Tay Cr.	92	4	19	20	0.9	602	241	6	117	1.3	745	12	5.1	0.0	0.0	2.8	14.7
Slim Cr.	532	5	135	71	0.5	625	1497	31	979	1.8	1043	38	1.9	0.0	3.1	1.9	12.9
Tako Cr.	182	4	87	30	1.9	527	470	8	408	2.2	608	58	5.1	0.0	0.0	3.2	14.6
Hospital Cr.	56	4	30	15	0.6	574	356	7	130	2.3	764	11	2.4	0.0	0.0	3.4	15.4
Wright Cr.	198	4	53	27	0.8	598	386	5	301	1.5	610	29	4.9	0.0	0.0	3.4	15.5
Averil Cr.	73	4	22	22	1.9	600	620	17	183	2.5	902	78	4.3	0.0	0.0	2.5	14.0
Wansa Cr.	291	4	69	54	0.3	642	1065	10	432	1.5	782	45	6.8	0.0	0.0	2.6	14.0
Tabor Cr.	147	5	71	29	0.9	565	680	8	195	1.3	698	35	5.3	0.0	0.0	3.1	14.6
Olsson Cr.	271	4	83	42	0.6	603	615	12	575	2.1	951	13	4.2	0.0	0.0	2.5	14.2
Stone Cr.	177	4	62	34	2.1	551	1193	16	275	1.5	781	19	2.2	0.0	0.7	2.5	13.8
Cale Cr.	192	4	79	27	0.9	558	823	11	302	1.6	717	65	4.6	0.0	0.0	2.8	14.1
Naver Cr.	901	5	259	99	0.5	533	1262	14	1301	1.4	767	17	3.9	0.0	0.2	2.4	13.5
RedRock Cr.	120	4	37	32	1.0	560	551	8	228	1.9	670	47	5.6	0.0	0.0	3.0	14.4
Albreda R.	410	5	91	31	0.6	731	2395	46	942	2.3	1128	8	0.9	4.0	22.4	0.2	11.9
Canvas Cr.	61	3	17	16	7.7	775	1650	52	132	2.1	1345	4	0.2	0.4	21.6	0.6	12.1

(Continues)

Table. (Continued)

Gazetted name	Area (km²)	Order	Magnitude	Mainstem Length (km)	Mainstem Gradient (%)	Min. elev. (m)	Relief (m)	Terrain slope (%)	Total stream length (km)	Stream density (km/km²)	Mean annual precip. (mm)	Lake influence (%)	Percent of Watershed Area Lakes	Ice	Alpine	Mean air temperature Ann. (°C)	July (°C)
Fishtrap Cr.	164	4	22	24	4.6	367	1287	20	301	1.8	547	27	1.6	0.0	0.0	2.9	14.0
Maka Cr.	216	4	44	35	1.2	804	1177	29	391	1.8	1528	23	1.1	0.0	1.6	3.3	13.9
Fadear Cr.	124	4	32	16	4.3	630	1242	27	161	1.3	563	18	0.1	0.0	0.0	3.2	14.3
Juliet Cr.	89	4	25	16	2.0	1013	1102	37	130	1.4	2455	3	0.1	0.0	15.1	2.8	13.4
Darlington Cr.	71	3	11	14	7.8	382	1283	17	150	2.1	579	7	2.1	0.0	0.0	3.4	14.9
Harper Cr.	188	4	56	26	1.1	636	1967	38	416	2.2	738	3	1.9	0.0	10.9	1.4	12.3
Nuaitch Cr.	84	3	14	15	4.1	501	1408	33	199	2.4	543	0	0.0	0.0	0.0	3.8	15.1
Otter Cr.	124	4	29	15	4.9	565	1407	22	120	1.0	1223	6	2.6	0.0	1.5	1.2	12.4
Lemieux Cr.	529	5	127	40	1.0	381	1509	21	993	1.9	625	64	7.4	0.0	0.0	2.5	13.4
Jamieson Cr.	238	4	38	34	3.1	352	1517	17	455	1.9	525	8	2.0	0.0	0.0	2.9	14.1
Mann Cr.	291	4	66	56	3.2	391	1581	18	572	2.1	789	44	3.3	0.0	0.4	1.9	12.7
Skuhun Cr.	233	5	70	33	4.2	399	1433	20		2.5	424	11	0.9	0.0	0.0	3.2	14.1
Mad R.	227	5	92	38	2.0	511	1405	26	429	1.9	1244	7	3.6	0.0	0.0	1.6	12.8
Louis Cr.	519	4	78	59	1.4	372	1772	28	806	1.6	548	11	0.6	0.0	0.4	3.2	14.4
Raft R.	766	5	345	81	1.1	405	2170	27	1551	2.0	1238	15	3.7	0.0	2.6	1.7	12.7
Barriere R.	1145	5	254	74	0.7	372	2231	29	1867	1.6	652	89	3.3	0.0	2.9	2.5	13.8
Guichon Cr.	1230	5	351	85	1.3	576	1424	13	2387	1.9	404	83	2.6	0.0	0.0	3.4	14.2
Spius Cr.	777	5	136	49	1.0	522	1734	29	1438	1.9	1174	9	0.6	0.0	4.4	3.4	14.2
U. Nicola R.	1506	5	569	99	0.6	629	1346	13	2689	1.8	549	64	4.7	0.0	0.0	3.5	14.4
Tranquille R.	442	4	102	59	2.1	336	1525	21	780	1.8	480	15	2.5	0.0	0.0	3.2	14.3
Coldwater R.	917	5	194	92	0.5	590	1525	25	1627	1.8	1068	15	2.0	0.0	2.6	3.9	14.7