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A Species Tolerance Index for Maximum Water Temperature

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A weighted species association tolerance index with respect to water temperature (WSATI-WT) is based on the final temperature preferendum (FTP) of each of the fish species present in a locale of a stream ecosystem. The WSATI-WT is a measure of the distributional consequences of "behaviour" or habitat selection of an interactive set of species with respect to temperature and extends the indicator species concept to an entire association of fishes. Several relationships were exploited to estimate the FTP of several species for which direct estimates were not available: FTP inferred directly from behavioral responses are found to be related approximately by a 1:1 ratio with optimal temperatures for growth, upper lethal temperatures estimated using ultimate upper incipient lethal temperatures,or critical temperature maximum, are related to the FTP by a straight-line relationship across species (within a limited temperature range). When the WSATI-WT was tested in the field, we found positive relationships between it and maximal summer habitat temperatures. The WSATI-WT can be used with observed maximum summer stream water temperatures to forecast change in index scores from a known reference community structure due to warming.

Key words: **habitat preference, fish distribution, temperature ecology, spatial/temporal comparisons, aggregated index**

Introduction

Fry (1947), Brett (1956), Reynolds and Casterlin (1979) and others suggest that the "pattern" of tolerances and preferences for temperature at an organismal level is broadly similar for different species of fish. The "patterns" for three species are shown in Fig. 1. These "patterns" are three dimensional — the implicit dimension in Fig. 1 relates to the degree of "competence" and "incompetence" for the organism at a particular point in the explicit two-dimensional space. "Competence", represented by various physiological and behavioral capabilities, is maximized at the final temperature preferendum (FTP) (Giattina and Garton 1982). It falls off steeply above and to the right of this peak, and falls off more gradually below and to the left of the peak. All points on this three-dimensional surface relate to a state of relative equilibrium with respect to "short-term acclimation" of the organism. We observed similar patterns for all species for which we had sufficient data (Lin 1995), and thus we defined the pattern depicted in Fig. 1 as an acclimation-response pattern.

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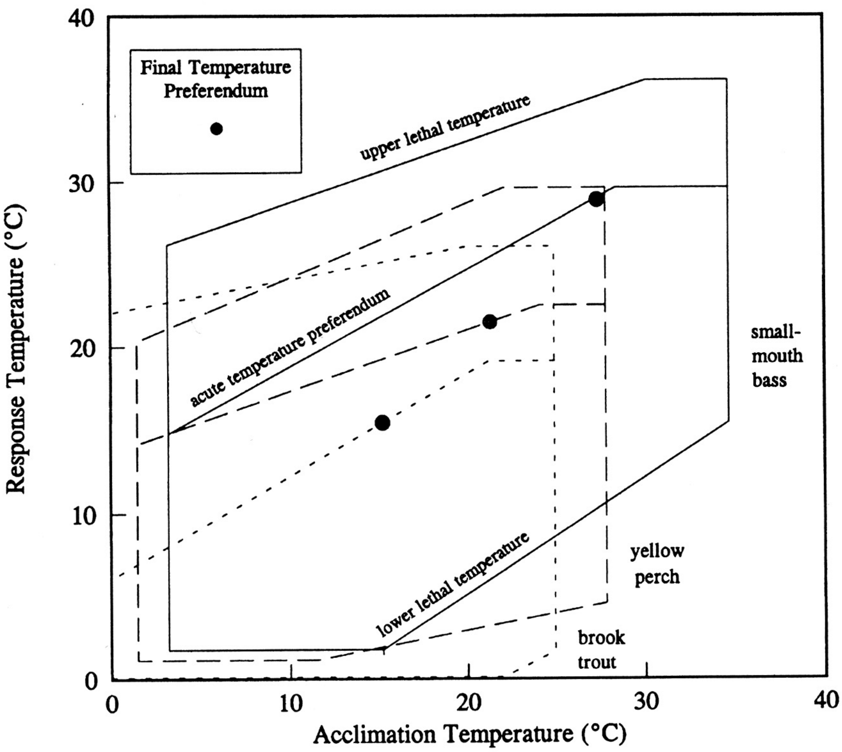

Fig. 1. Acute temperature preferenda and upper and lower lethal temperatures for smallmouth bass, yellow perch and brook trout. The polygons of three species are redrawn from diagrams in Brett (1956), Cherry et al. (1977) and Wismer and Christie (1987). The three slanted lines for the smallmouth bass polygon are labelled; the corresponding lines for the other species are the same but are not labelled for clarity.

An acclimation-response pattern is derived from the results of laboratory studies,but field studies can provide strong support (Magnuson et al. 1979; Eaton et al. 1995). Interactions between the temperature-related features of physiology and ecology of organisms have been explored for various fish taxa (Brett 1971; Beitinger and Fitzpatrick 1979; Kellogg and Gift 1983). McCauley and Casselman (1980) and Jobling (1981) inferred a general relationship between the FTP and OTG across a number of fish species.

Fish appear to be more tolerant of temperatures below their FTP than temperatures above their FTP. Presumably because of a greater risk to fish at temperatures more than a few degrees above their FTP, they are more likely to be found in habitats with temperatures below their FTP.

We propose and assess an aggregated index to measure the effect of temperature on fish associations. A stream reach may change with respect to maximum summer water temperature but not change with respect to other water quality variables. We explore the relationship between the WSATI-WT for a fish association and oserved maximum stream habitat temperatures (OMHT) for Toronto area streams.

We define "fish association" as the mix of species at a particular location, at a particular time. Wichert (1995a, 1995b) developed a conceptually similar index, the weighted species association tolerance index with respect to water quality (WSATI-WQ), in which the responses of individual fish species to water quality variables other than temperature are assessed and aggregated to show a response of the whole fish association to changes in water quality. In Toronto area streams there are different species which fall into each of the following FTP and water quality categories: relatively cold FTP and high water quality, relatively cold FTP and low water quality, relatively cool FTP and high water quality, relatively cool FTP and low water quality, relatively warm FTP and high water quality, and relatively warm FTP and low water quality. Thus, it is conceptually possible for fish associations to demonstrate ecologically independent responses to water temperature and other water quality variables.

Stream locales encompassing a broad range of water quality conditions, maximum summer water temperatures and flow volume are not found in the Toronto area. Given these constraints, the ecological independence of water quality and water temperature cannot be empirically tested in a definitive way for Toronto area streams. Wichert (1994) and Wichert and Regier (in press) tested for ecological independence in an approximate way and found no significant relationship between fish species responses to water quality variables other than temperature and stream order (a surrogate measure for stream temperature).

In this study we test the applicability of Jobling's generalizations — that interrelate separate estimates of FTP, optimal temperatures for growth (OTG) and upper lethal temperatures — with fish species in Toronto area streams.

- We use the quantitative generalizations about FTP, OTG and upper lethal temperatures that we inferred for local species to provide best available estimates of FTP for calculating a weighted species association tolerance index with respect to water temperature (WSATI-WT) of the fish association.
- We then use field data (fish abundance and water temperatures) collected in 1992–93 in two locales in the Toronto area, for which sampling criteria were quite strict, to compare stream temperatures with WSATI-WT scores (one on the Credit and one on the Humber River).
- We compared the relative abundance of fish species collected at three sites in Duffins Creek — in the headwaters, a middle reach and near the mouth — that were sampled nearly annually for 8 to 20 years to test year-to-year changes in the fish association with respect to water temperature. These data were also used to determine if the preferred temperature of a fish association is influenced by maximum temperature in each summer or by the maximum temperature over several summers.

• Finally we test the feasibility of this approach for regional studies by using synoptic data from fish surveys in 1984–85 on three basins of the Toronto Area Waters — upper Credit and east Humber Rivers and Duffins Creek — to obtain the WSATI-WTs. The WSATI-WT scores were compared with OMHT, collected in 1991–93 from the same sites as the fish data were collected in the 1984–85 survey.

The WSATI-WT would be useful for inferring changes in ecological conditions which influence stream water temperatures on a fish association. Some of these ecological conditions include: reduction in shade from riparian vegetation, overflow from impounded waters, — ponds, lakes, reservoirs — change in base flow in summer due to reductions in cold water supply from aquifers, and increased surface run off of warm waters from urbanized areas in summer.

Development of the WSATI-WT

In this section we describe some of the conceptual underpinnings and terms for the WSATI-WT, the protocol we followed for selecting data for the model, some statistical relationships between the critical temperatures of different fish species useful for estimating missing FTP values for some species, and the mathematical formula for the WSATI-WT.

Terms

Fry (1947) defined the FTP of fish species as: "that temperature around which all individuals will ultimately congregate [after 24 hours or more], regardless of their experience before being placed in the gradient" and "that temperature at which the acute temperature preferendum (ATP) is equal to the acclimation temperature." The ATP is usually measured following a short period of acclimation (i.e., less than two hours).

Upper lethal temperatures for fish species have been estimated using three conventions: upper incipient lethal temperature (UILT), ultimate upper incipient lethal temperature (UUILT) and critical temperature maximum (CTM). At the UILT, 50% of the organisms acclimated to that temperature for about 4 to 7 days cannot survive; beyond the UUILT, further acclimation has no effect on survival; and at the CTM, muscle spasms or loss of equilibrium occurs while water temperature is raised at 1°C/min. The CTM for a species (as in an expanded version of Fig. 1) is generally higher than the UUILT, which is higher than UILT; trends in these three measures relative to acclimation temperature are approximately parallel (Reynolds and Casterlin 1979). A somewhat similar pattern has been inferred with respect to FTP across species (Jobling 1981).

Description of WSATI-WT Model

We derived the WSATI-WT using data on the FTP, UUILT and CTM. The WSATI-WT is defined mathematically as

$$WSATI-WT=\sum_{i=1}^{N} A_i FTP_i,$$

where $A_i = n_i/\sum_{i=1}^{N} n_i$, the relative abundance of each species as a percent of total catch as estimated from data obtained by using a set of sampling gear that yields a relatively unbiased sample; n_i is the the number of individuals of species i; N is the number of species found; and FTP_i is the FTP of each species i. This index is an overall weighted mean of the FTP of the fish species present at a sampling site on a given occasion, normalized or standardized to a single fish basis by means of the A_i term. Note that larval fish less than about 2 cm length passed through the gear and were not sampled in the present study. Fish data were collected in the summer months from June to early September.

From the literature, we collected experimental laboratory data on preferred, optimal and upper lethal temperatures for 60 species of fish found in the Toronto area waters. The Toronto area waters here include the Credit, Humber, Don and Rouge rivers and Duffins Creek together with smaller streams, coastal wetlands and the contiguous waters of Lake Ontario within 5 km of the shoreline. The families of fish found in the Toronto area waters include *Petromyzontidae*, 1 species; *Amiidae*, 1 species; *Clupeidae*, 1 species; *Salmoninae*, 8 species; *Coregoninae*, 2 species; *Osmeridae*, 1 species; *Esocidae*, 2 species; *Catostomidae*, 2 species; *Cyprinidae*, 17 species; *Ictaluridae*, 3 species; *Anguillidae*, 1 species; *Cyprinodontidae*, 1 species; *Gasterosteidae*, 1 species; *Percopsidae*, 1 species; *Percichthyidae*, 2 species; *Centrarchidae*, 7 species; *Percidae*, 6 species; *Sciaenidae*, 1 species; *Cottidae*, 2 species. Since estimates of critical temperatures from field studies may be influenced by factors such as light, food availability, inter- and intra-specific interactions, we only used temperature data from standardized laboratory studies. The data, many of which come from Wismer and Christie (1987), include measures of FTP and OTG in 29 species, of FTP and UUILT in 45 species and of FTP and CTM in 19 species (Wichert 1995a).

We plotted FTP separately against OTG, UUILT and CTM for fish found in the Toronto area waters (Fig. 2). Based on previous studies (Beitinger and Fitzpatrick 1979; McCauley and Casselman 1980; Jobling 1981; and Kellogg and Gift 1983), we expected the ratio of FTP to OTG to be about 1.0, and the ratio we found was 0.997 (Fig. 2). We used an independent variable to fit the parallel trends of UUILT and CTM relative to FTP. The ratio of OTG to FTP and regression relationships between UUILT and FTP and CTM and FTP were used to estimate preferred temperatures for species for which the FTP was not published. The total set of FTP was used to calculate WSATI-WT scores.

Estimates of FTP for the WSATI-WT

For species where the FTP is not available, if some other information such as OTG, UUILT or CTM is available, the FTP can be estimated from the regression relationships:

$$FTP = 0.997\ OTG;\ n = 29,\ r^2 = 0.99;\ p < 0.001;$$
$$FTP = -15.3 + 1.22\ UUILT;\ n = 45,\ r^2 = 0.83,\ p < 0.001;$$
$$FTP = -17.5 + 1.22\ CTM;\ n = 19,\ r^2 = 0.83,\ p < 0.001;$$
$$\text{and } CTM = 1.80 + UUILT.$$

Data and statistics relevant to goodness of fit are included as Appendix D of Wichert (1995a). The FTP for 52 of 60 species were compiled directly from data obtained from various laboratory experiments. Final temperature preferenda for six of the eight remaining species were estimated using UUILT data and the regression relationship between UUILT and FTP, and for two species,FTPs were estimated from the regression relationship between CTM and FTP.

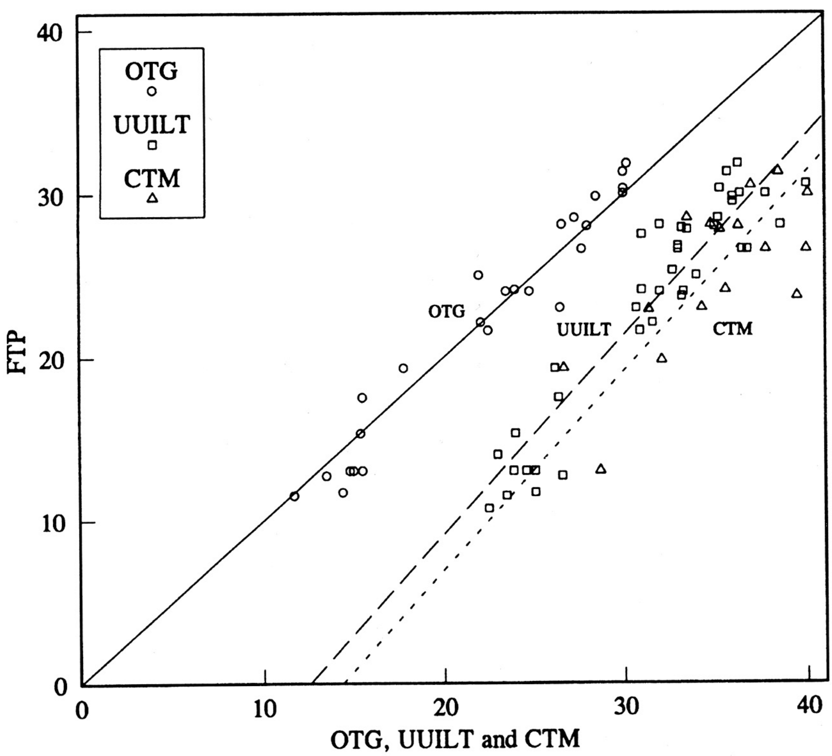

Fig. 2. Final temperature preferenda (FTP), optimal temperatures for growth (OTG), ultimate upper incipient lethal temperatures (UUILT), and critical temperature maximum (CTM) for fishes of the Toronto area.

Application of the WSATI-WT Using Field Data

In this section we outline the protocol we followed when we sampled streams for fish and when we collected OMHTs. Detailed sampling procedures at two specific sampling locations are described and data sources for regional fish collections are provided. We also show the results of applying the WSATI-WT at two spatial and temporal scales.

Sources of Data

The fish data used to test the WSATI-WT at the two locales on the Credit and Humber rivers were collected on three occasions in 1992, and twice in 1993. In order to obtain information when the influence of insolation, ambient air temperature and base flow on stream temperature was maximized, we sampled streams when there had been no rain in the previous 7 days and when the air temperature during each of the previous 5 or more days reached 25°C or higher. It became apparent early in 1992 that the summer might be relatively cool, hence the criterion on when to sample was relaxed and sampling was done in three relatively warm periods. By examining 1992 data, after the fact, we found that the three selected periods for the Credit and two of the three selected periods for the Humber had been the warmest of the summer (Environment Canada 1993, unpublished data). Early in the summer of 1993, it appeared that the summer temperature regime might be normal, so the original criterion was used.

The same criterion on when to sample was used for collecting OMHTs from 60 stations on Toronto area streams in 1991–93. Means of the three OMHT estimates from each of the 60 stations (one estimate for each year) were calculated for the 3 years and used as OMHT in subsequent regional analyses.

The collection of fish data from the three sites on Duffins Creek was supervised by J.B. Falls of the University of Toronto. (One of us (Wichert), helped supervise collection of these data from 1991–93.) The headwater site was sampled between 1970 and 1979; the one in the middle reach from 1966 to 1993; and the site at the mouth from 1966 to 1984. The sampling methodology employed in these surveys was similar to the methodology of other surveys reported here (see Methods below) except that these samples were collected in the autumn and others were collected during the summer.

In general, human impacts to the stream in these three areas have been smaller than other parts of the Toronto area waters. However some estate development occurred in the vicinity of the headwater site. The middle reach site was in a multiple-use Conservation Area park.

The data on the distribution of fish species in the upper Credit River, east branch of the Humber River and Duffins Creek, were collected during a comprehensive survey by Steedman in 1984–85 (Steedman 1987). All fish survey data were collected according to a sampling protocol which was generally consistent with sampling elsewhere with respect to season, hydrological considerations, site selection, sampling effort and gear selection (Wichert 1995a), but in the regional collections by Steedman (1984–85), air temperatures did not necessarily reach 25°C or higher on each of the 5 days prior to sampling.

Methods

Test of the WSATI-WT at Two Locales in the Toronto Area Waters

The WSATI-WT was tested at two locations: Credit River station 16, approximately 1 km downstream from Erin (43° 53′; 79° 46.5′) and Humber River station 33, about 1.5 km downstream from Bolton (43° 53.0′; 79°43.5′) (Wichert 1991, Fig. 1). Fish species present at one or both of these locales were members of the *Petromyzontidae, Salmoninae, Catostomidae, Cyprinidae, Ictaluridae, Gasterosteidae, Centrarchidae, Centrarchidae, Percidae* and *Cottidae* families.

The Credit River study locale was approximately 15 km from the headwaters and was about 8 m wide and 0.7 m deep at the deepest place. Substrate comprised sand and gravel with some cobble of about 10–15 cm in diameter. Mean discharge for the summer months (June, July and August) from 1983 to 1990 (the only period for which discharge data were available) was 0.36 m^3s^{-1}. The upstream reaches mostly flowed in wooded areas with some low intensity agriculture. The stream at the study locale was well shaded with mature cedars and willows.

The Humber River study locale was about 40 km from the headwaters and was about 15 m wide and 0.5 m deep at the deepest spot. Substrate comprised sand and gravel. Mean discharge for the summer months (June, July and August) from 1967 to 1988 (the only period for which discharge data were available) was 1.36 m^3s^{-1}. Many of the upstream reaches were in agricultural areas with some woodlots. The riparian vegetation at this locale was dominated by 1 m tall grasses that provided little shade to the stream.

At each "locale" a cold tributary flowed into the warmer mainstream of the respective rivers. Three different temperature zones, each with a "sampling site", existed at each locale. At both locales: the mainstem above the tributary was relatively warm; the tributary was relatively cold; and the mainstem below the tributary, i.e., in the mixed zone, was relatively cool. These locations were sampled three times during the summer of 1992 and twice during 1993. Locales were sampled between 12:00 and 16:00 and OMHT data were taken when the fish collections were made.

We set blocking nets at each locale to prevent the movement of fish between the three sampling sites and then sampled the sites using a combination of backpack electroshocker, dip nets and seines. We performed a single pass moving upstream in each of the three sites, sampling all representative habitats. Based on calculations using data collected in 1984 and 1985 from 196 stations on streams in the Toronto area (Steedman 1988), we inferred that the probability of catching species found at the Credit and Humber River stations using these capture methods ranged from 0.67 (for mottled sculpin, *Cottus bairdi*, and rainbow trout, *Oncorhynchus mykiss*, to 0.94 for white sucker, *Catostomus commersoni*). The length of each within-site sampling area was about 100 m. We kept the fish in live wells before identifying, counting and returning them to their respective sites. We did not remove the blocking nets until all three sites were sampled. One of our self-enforced constraints was that our sampling should be relatively non-destructive of fish and their habitats; this is now the preferred practice in such research studies and in field surveys.

We calculated regression relationships with the WSATI-WT and OMHT data for the Credit and Humber River locales for 1992 and 1993. An independent variable was used to represent data from the 2 years. An example showing the list of species captured, the variables and calculations of the WSATI-WT for a locale on a particular day is in Table 1.

Table 1. Example of the calculations to estimate the WSATI-WT at three sites in a locale on the Humber River near Bolton on 12 August 1993.

		Sample site		
Species name	FTP_i[a]	Upstream mainstem n_i[b]	Downstream mainstem n_i[b]	Cold tributary n_i[b]
Mottled sculpin	16.5	1	19	68
Blacknose dace	19.2	1	17	0
Rainbow trout	19.3	0	0	2
Rainbow darter	19.8	0	6	2
Faintail darter	20.3	19	42	4
Longnose dace	20.6	3	57	20
Creek chub	20.8	12	35	31
Brook stickleback	21.3	0	2	7
River chub	21.7	4	0	15
Common shiner	21.9	1	1	0
Johnny darter	22.9	4	4	1
White sucker	24.0	1	3	8
Brown bullhead	24.9	1	1	0
Stonecat	25.1	8	4	0
Rock bass	26.6	17	15	0
Northern hogsucker	26.6	0	1	0
Bluntnose minnow	27.9	3	0	0
	Totals	75	207	158
	WSATI-WT	22.9	20.7	19.2
	Habitat temperature	25.5	22.5	19.5

[a]FTP_i is final thermal preferendum of each species and [b]n_i is the number of individuals of each species sampled.

Test of the WSATI-WT at Three Locales in Duffins Creek

Except for samples collected in 1992 and 1993, the maximum summer stream temperatures for the relevant sites were not available for the time during which the fish data were collected, so air temperatures collected by Environment Canada from Toronto International Airport, about 50 km west of the sampling sites, were used as a surrogate. We calculated the average of the maximum air temperature of the 6 consecutive days with the highest daily maximum air temperature and compared these with the WSATI-WT scores for the three sampling sites (Wichert 1995). We expected the relationship between maximum annual air temperature and WSATI-WT to be positive with a slope significantly different from zero if WSATI-WT scores were strongly influenced by year-to-year changes in maximum air temperatures.

Test of the WSATI-WT at the Subwatershed Level

We compared OMHT with WSATI-WT scores for parts of the Credit, East Humber and Duffins watersheds, where the fish associations were collected by Steedman (1988) during the summer months of 1984–85. During the summers of 1991–93 stream temperatures were collected from each of 60 sites in the basins listed above during hot and dry periods, according to criteria listed above. Our hypothesis was that the WSATI-WT index from the 1984–85 data should be positively related to the OMHT at the same site from the 1991–93 data. In this comparison, OMHT was considered an independent variable since direct stream temperatures were taken.

Results

Test of the WSATI-WT at Two Locales in the Toronto Area Waters

Humber River

There are positive, but not coincident, relationships between the OMHT and the WSATI-WT scores for the Humber River for 1992 and 1993 (Fig. 3). We compared the regression data of the WSATI-WT and OMHT for 1992 and 1993 using an independent variable to represent data from the 2 years and found the between-year-difference, 3.90, to be significantly different from 0 ($p < 0.01$). The range in OMHT from warm to cold sampling sites within each year was about 6°C. The maximum air temperature at the time of sampling was about 6°C cooler in 1992 than 1993. This was consistent with OMHT which were also about 6°C cooler for warm, cool and cold sites, respectively, in 1992 than they were in 1993 (OMHT and WSATI-WT data are in Wichert 1995a). A possible reason for the discrepancy between the data sets in the 2 years is that the fish association at a locale is adapted to the average maximum habitat temperature over a series of years, which was approximated in 1993. Thus, the WSATI-WT calculated from the fish association at a particular locale may provide an estimate of the long-term average OMHT at that site. For the 2 years of

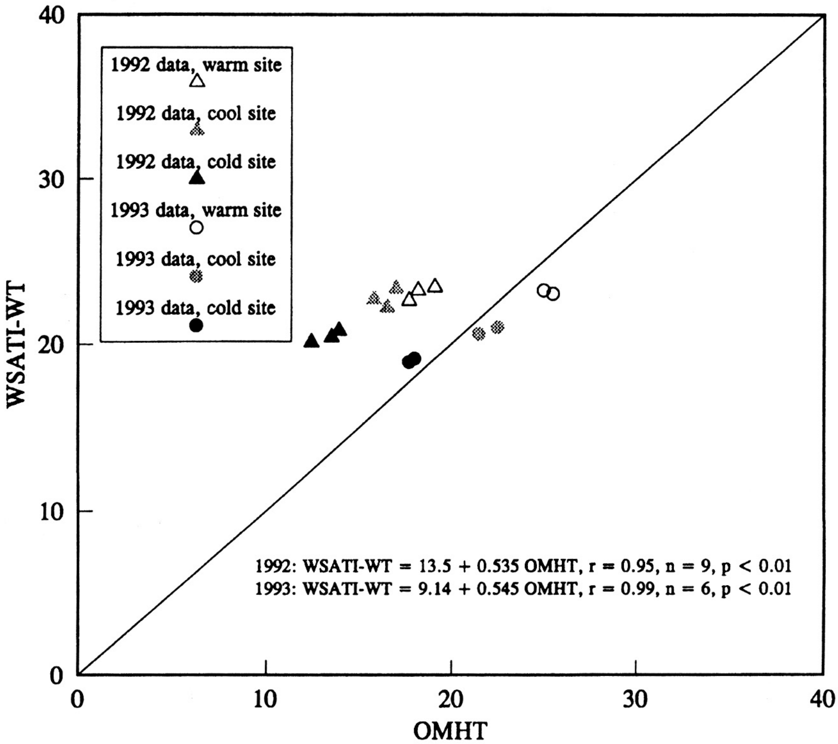

Fig. 3. Relationship between OMHT and WSATI-WT values for the Humber River locale. Regression lines are not plotted; instead, the line of direct proportionality is provided for visual reference.

sampling, some 90 and 98% of the variance between OMHT and WSATI-WT scores were explained, (see Wichert 1995a).

Credit River

A positive relationship exists between OMHT and the WSATI-WT scores for the Credit River (Fig. 4). The range in mean OMHT from warm to cold sites within each year was about 5°C and the difference in mean air and OMHT in their respective stream temperature zones between the 2 years was about 1°C (OMHT and WSATI-WT data are in Wichert 1995a).

We compared the regression data of the WSATI-WT and OMHT for 1992 and 1993 using an independent variable to represent data from the two years and found the between year difference, 0.726, to be not significantly different from 0 ($p = 0.22$). For the two years of sampling it appears that some 75 and 90% of the variance between OMHT and WSATI-WT scores were explained.

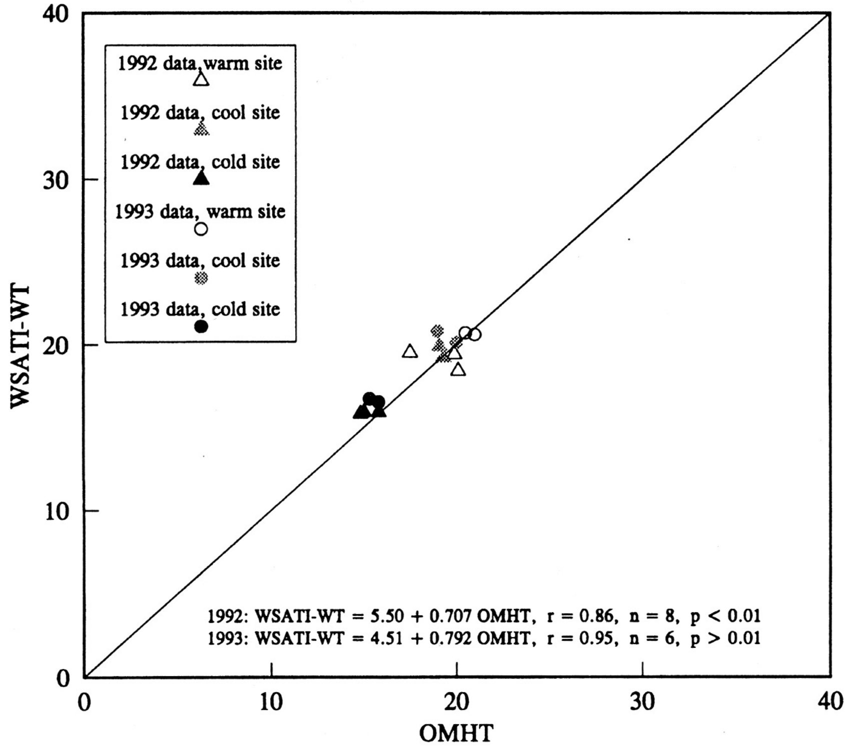

Fig. 4. Relationship between OMHT and WSATI-WT values for the Credit River locale. Regression lines are not plottedl; instead, the line of direct proportionality is provided for visual reference.

Three Sites on Duffins Creek

The WSATI-WT scores showed no significant increase or decrease at any of the three sites on Duffins Creek from 1966–93 (Fig. 5). This suggests that the preferred temperature of the fish association is influenced more strongly by long-term maximum temperatures than by annual maximum temperatures. These results are consistent with those reported by Wichert and Regier (in press).

The WSATI-WT scores for the headwater and middle reach site appear more tightly clustered around the regression line than WSATI-WT scores for the site near the mouth of Duffins Creek. The site at the mouth may be influenced by seiches in Lake Ontario (Kauffman 1991), which cause cold water from the lake to inundate Duffins Creek as far as 1 km upstream from the mouth. The WSATI-WT scores for the headwater and middle reach sites are somewhat below the summer 6-day mean maximum air temperatures because they are influenced by ground water which flows at approximately 9–10°C year-round.

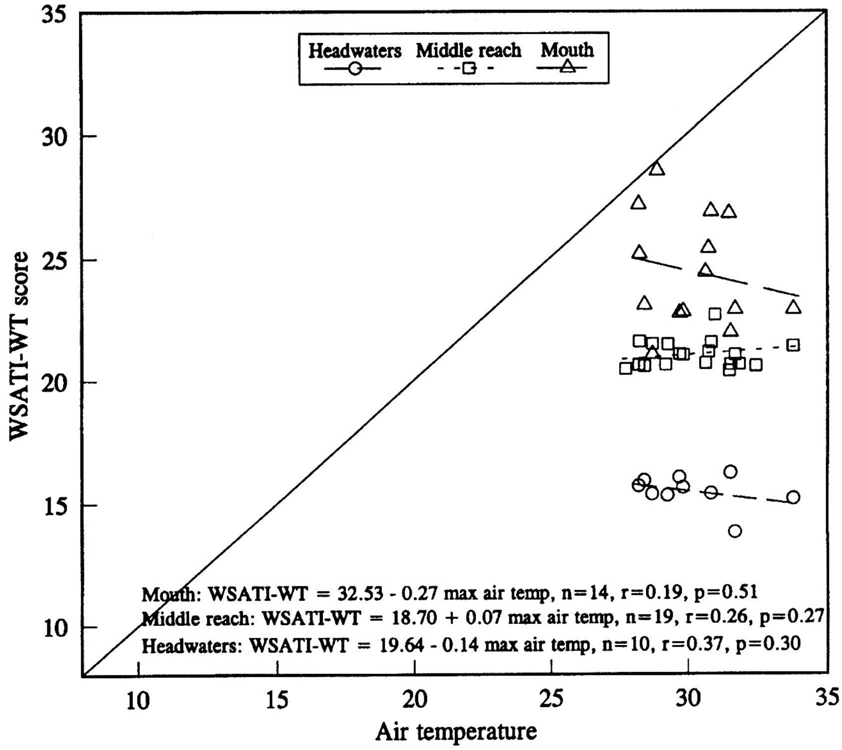

Fig. 5. Relationship of WSATI-WT scores for three locales in Duffins Creek — one near the headwaters, one in the middle reaches and one near the mouth — and the mean of the maximum air temperatures of the warmest 6 consecutive days of each summer from 1966–93 . The air temperatures were taken at a location 50 km west of the Duffins Creek watershed. Each data point on the figure represents an air temperature and a WSATI-WT score for one year between 1966 and 1993.

Basin Tests of the WSATI-WT

When tested across the three subwatersheds, WSATI-WT scores from data collected in 1984–85 appear correlated with OMHT data collected during warm periods in the summers of 1991–93 (Fig. 6). We did not attempt to control for stream flow, substrate, physiography, riparian vegetation or land use; these and other variables likely contribute to the unexplained variance. A simple linear regression model and a ratio model (Snedecor and Cochrane 1989) were fitted to subsets of the data as shown in Table 2. The ratio model is defined mathematically as

$$R = \frac{\Sigma WSATI\text{-}WT_i}{\Sigma OMHT_i}$$

where R is the ratio coefficient.

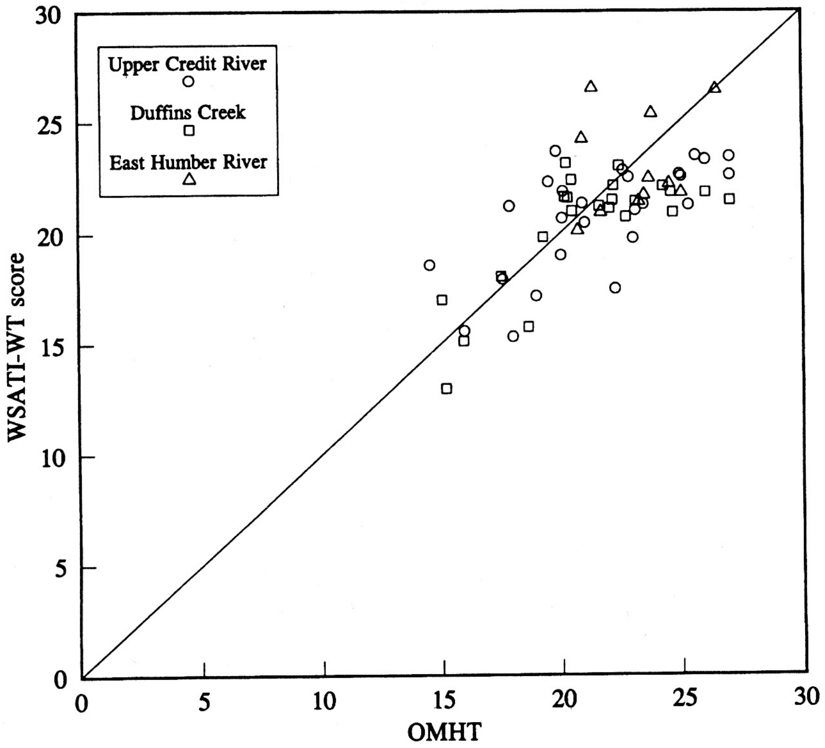

Fig. 6. WSATI-WT scores using fish data collected by Steedman in 1984–85 and average observed maximum habitat temperatures (OMHT) for three subwatersheds of the Toronto area waters collected in 1991–93 during summer at times when stream temperatures were thought to be highest. Line of direct proportionality is included for visual reference purposes only; regression and ratio estimates are provided in Table 2.

Table 2. Regression and ratio coefficients and 95% confidence interval for some individual subwatersheds of the TAW and overall comparisons between OMHT and WSATI-WT scores; na means not applicable. Fish data are from Steedman (1987); see also Figure 6.

Type of estimate	Subwatershed	N	r^2	Constant	Coefficient (± 95% C.I.)
Regression	Credit R.	26	0.45[a]	10.3	0.479 (0.225)
	E. Humber R.	11	0.06	16.3	0.289 (0.885)
	Duffins Ck.	23	0.56[a]	7.22	0.620 (0.250)
	Combined	60	0.46[a]	8.61	0.569 (0.162)
Ratio	Combined	60	na	0	0.966 (0.027)

[a]Significant at $p < 0.05$.

We infer that WSATI-WT scores from generalized summer sampling are positively correlated with OMHT data collected at the warmest times of the summer, but which mathematical model is most appropriate is unclear to us.

Discussion and Synthesis

In this study we proposed an aggregated index (relative abundance and temperature preference) to measure the effects of temperature on fish associations and assessed the index at two different spatial scales. The index was based on the premise that a species would prosper in waters that reached its FTP but did not exceed it by more than a few degrees Celsius. The reliability of the WSATI-WT is dependent on obtaining accurate estimates of the FTP for each species. In the following discussion we provide some theoretical evidence to support the relationships between FTP, OTG and upper lethal temperatures (UUILT and CTM), which we used to estimate the FTP for each of the fish species.

Evolutionary Considerations

Temperature affects organisms at all levels of biological organization, including behaviour, physiology and biochemistry (Fry 1971; Hokanson 1977; Hochachka and Somero 1984; Cossins and Bowler 1987). In this study we focused on "behavioral fitness" or "competence" in terms of preferred temperature, or FTP, and maximum physiological capacity in terms of optimal temperatures for growth. Through adaptation, behavioral temperature preference and physiological optimum with respect to temperature should be closely interrelated in ectotherms since the body temperature selected by them has profound effects on the physiological capacity and enzyme dynamics (Brett 1972; Beitinger and Fitzpatrick 1979; Huey and Stevenson 1979; Huey 1982; Hochachka and Somero 1984).

Bayley and Osborne (1993) found that stream fishes moved up to 15 km within a year to recolonize streams following drought conditions and stream desiccation. Peterson and Bayley (1993) found that fish recolonized short reaches of streams (50 m) to preremoval composition and abundance within 60 to 270 hours of removal. Thus, it seems reasonable that fish may move to find suitable habitat. Since fish tend to maximize growth, at least until the age of sexual maturity (Brett 1972), and fish in the streams that we studied appear to be relatively free to move up and downstream and seek out habitat temperatures close to their FTP, we judge that close temperature coadaptation is relevant to this study. Our observed value of 0.997 for the ratio of FTP to OTG is empirically consistent with the expected ratio of 1.0. Our comparison of FTP and OTG (Fig. 2) is also consistent with the empirical relationship for various species of fish (Beitinger and Fitzpatrick 1979; McCauley and Casselman 1980; Jobling 1981; Kellogg and Gift 1983).

Ecological Considerations

It has long been recognized that the presence or absence of a fish species at a locale in summer months depends, *inter alia*, upon the water temperature. Christie and Regier (1988) tested a generalization by Magnuson et al. (1979) and found empirical support for a relationship between abundance of a species in different lakes and the temporally weighted size of habitat with temperatures close to the FTP of that species. Meisner (1990) and others have found from field studies that fish try to avoid temperatures more than a few degrees above their FTP. From a comparison of the patterns in Fig. 2, it appears that the difference, across species, between FTP and upper lethal temperatures (UUILT and CTM) decreases as preferred temperature increases. This decrease relates to the acclimation-response patterns of Fig. 1 in which the degree of "competence" falls off more steeply above and to the right of the FTP than below and to the left. The relationship between upper lethal and preferred temperatures and the asymmetry of the fitness of fish species above and below the FTP suggests that fish are more likely to be found at or slightly below their FTP than above it during warm weather periods.

The data from the Humber River locale (Fig. 3) is consistent with the notion that the fish association may not redistribute itself longitudinally along a reach each year but may be broadly similar from year to year and be adapted so that the WSATI-WT relates to the across-year average OMHT for a particular locale. This is consistent with findings from the second part of the study which shows no significant relationship between WSATI-WT score and the mean of the maximum air temperatures of the 6 warmest days each year (Fig. 5). Trends through time for WSATI-WT scores and the mean of the maximum temperatures of the 6 warmest consecutive days each year are approximately parallel with slopes not significantly different from 0 (Wichert and Regier, in press). This finding provides additional evidence that the fish association may be adapted to across-year OMHT values.

Conclusions

The expected weighted species association tolerance with respect to temperature (WSATI-WT) scores that were calculated from fish samples collected at several locales were related to the summer observed maximum habitat temperature (OMHT). The index can be used to forecast the continued suitability of a given temperature regime for a suite of known fish species based upon FTP, given predictions in change in stream temperatures.

It is possible that absolute abundance data, i.e., quantitative density or biomass data, would provide more accurate WSATI-WT scores but this question is not addressed here. Relative abundance data are less difficult to collect than absolute abundance data. Results from several spatial and temporal scales in this study suggest that the WSATI-WT — which employed relative abundance data — is a practical, rapid assessment tool to forecast influence of changes in maximum summer stream temperatures on fish associations.

Field tests of WSATI-WT using fish abundance data confirm that this index is useful to explain and evaluate the suitability of stream temperature conditions for certain fish associations at the two levels of spatial scale. By comparing the amount of variance explained by the relationship between OMHT and WSATI-WT, it appears that the importance of habitat temperature alone as influencing the species composition of the fish association decreases at larger spatial scales.

The WSATI-WT has been applied in another regional study of Toronto area streams by Wichert and Regier (in press). They found that at sites in subwatersheds where land use was not currently pristine, but had not changed significantly over the past four or five decades, the WSATI-WT scores were relatively constant through time (Wichert and Regier, in press).

A conceptually similar index, the WSATI-WQ, has also been tested with fish in Toronto area streams and is also being applied (Wichert 1994; 1995a; 1995b). A third index, WSATI-habitat structure (-HS), could presumably be developed by numerically scoring the preference of fish species for "habitat structure" as described generically (Sedell et al. 1991).

WSATI indices are relatively transparent, in that attributes used to rank species are readily defensible ecologically, do not require site-specific calibration, and the results are easy to interpret and appear to be relatively independent from each other with respect to ecosystem phenomena of practical interest (Wichert 1994; 1995a; Wichert and Regier in press). These qualities give the WSATI approach an advantage over others, such as multivariate statistics and the index of biotic integrity, which have been used to assess changes in biotic communities (Fausch et al. 1990). A set of three relatively independent indices — WT, WQ, HS — would be helpful for assessing effects of various kinds of human disturbances on streams and their fish associations.

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