Ecology of Freshwater Fish 2011: 20: 431–437
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ECOLOGY OF
FRESHWATER FISH

The influence of land cover composition and groundwater on thermal habitat availability for brook charr (*Salvelinus fontinalis*) populations in the United States of America

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Accepted for publication December 30, 2010

Abstract – Brook charr (*Salvelinus fontinalis*) is a sentinel fish species that requires clean, cold water habitats generally resulting from landscapes that allow for surface water flows devoid of sediment and contaminants and high groundwater discharge of cold water. As such, brook charr are impacted by land cover changes that alter stream temperature regimes. We evaluated brook charr populations across their eastern and midwestern range in the United States with reference to thermal habitat availability in relationship to land cover and per cent baseflow. We found that while forest cover does protect brook charr thermal habitat, high levels of groundwater discharge can allow for increased levels of agriculture within a watershed by keeping the water cold in spite of warm ambient summer temperatures. Our study concludes that with enhanced communication among land, water and fisheries managers, society can provide for sustainable stream salmonid populations despite increased threats on cold water resources.

Key words: Brook charr; land cover; groundwater

Introduction

Brook charr (*Salvelinus fontinalis*) is the only charr species native to eastern North America (Karas 1997). The native brook charr range in the United States of America (U.S.) extends from the Great Lakes region in the Upper Midwest (Minnesota, Wisconsin and Michigan) to the north-east (Maine to Maryland) and south along the Appalachian Mountain Chain to northern Georgia (Fig. 1; MacCrimmon & Campbell 1969). In the United States, brook charr have high cultural, economic and ecologic value along with utility as an indicator of the existence of high cold water quality systems (EBTJV (Eastern Brook Trout Joint Venture) 2006). Over the past 200 years, native U.S. brook charr populations have experienced dramatic population declines and reduction in range because of landscape disturbances within the watershed attributed to human development, such as urbanisation, agriculture, logging and mining (MacCrimmon & Campbell 1969; Marschall & Crowder 1996). Brook charr are a cold water, stenothermic species, exhibiting a narrow range of preferred water temperatures between 12 and 19 °C (Fry et al. 1946; Cherry et al. 1977). Studies have determined that brook charr are able to survive in water temperatures between 0 and 25.3 °C (Fry et al. 1946; Karas 1997); however, the physiological stress of living outside of the preferred temperature range increases susceptibility to predation and disease and has been shown to inhibit feeding, growth and reproduction (Brett 1956; Swift & Messer 1971; Giller & Malmqvist 1998). Because prolonged warming of brook charr habitat may eventually lead to population declines or

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doi: 10.1111/j.1600-0633.2011.00487.x

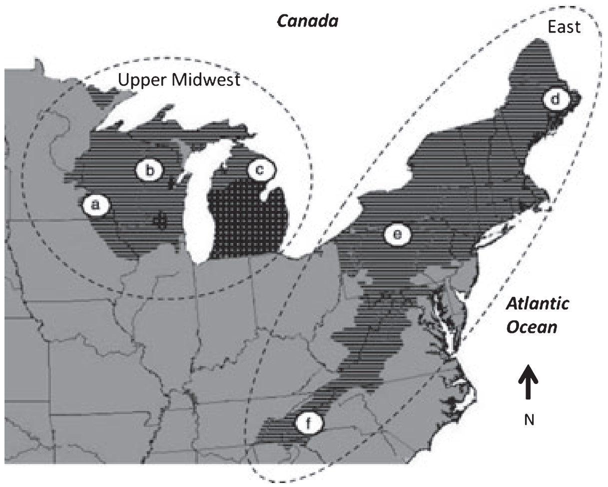

Fig. 1. Historic range of brook charr (*Salvelinus fontinalis*) in the Upper Midwest and Eastern United States (hatched; based on MacCrimmon & Campbell 1969) plus naturalised populations in lower Michigan and Wisconsin (dots). Six study sites highlighted, which contain intact brook charr populations: (a) West Indian Creek, Minnesota (b) East Branch of the Eau Claire River, Wisconsin (c) Au Sable River, Michigan (d) Old Stream, Maine (e) Satterlee Run, Pennsylvania (f) Mashie Stomp Creek, North Carolina.

extinctions (Raleigh 1982), understanding the factors that control water temperature in brook charr streams is a crucial component in this species' ecology, production dynamics and management, which is the principal focus of this paper.

The determinants of stream temperature, or thermal drivers, as specified by Sullivan & Adams (1991), can be classified into three broad categories of climate, geology and land cover. These drivers affect stream temperature through different pathways in the hydrologic cycle. Specifically, precipitation enters the stream system either directly as surface water runoff or infiltrates through the ground (percolation) and enters the stream through the underlying, colder groundwater aquifer. Water derived from the groundwater aquifer constitutes a stream's baseflow. Although baseflow fluctuates seasonally throughout the year, the groundwater aquifer provides the nearby stream with a relatively constant, cold supply of water. Thus, groundwater discharge acts to maintain minimum flows and relatively stable temperature regimes within a stream whereas surface flow is directly affected by ambient air temperature which is dictated by the regions climate and land cover at any particular point in time.

Geologic structure within the watershed significantly influences groundwater recharge rates and thus stream temperature (Stanford & Ward 1993). In general, higher elevation sites are collection areas (sources) of groundwater while lower elevation sites are groundwater sinks (Winter 1998). Additionally, soil permeability affects the amount and speed water percolates into the groundwater aquifer (Cey et al. 1998). Higher recharge rates equate to a larger contribution of groundwater, adding to the total stream flow and ultimately more stable, cold discharge into streams. Fine soils, clay or bedrock in the catchment allow less water to percolate into the aquifer, decreasing groundwater recharge while generating greater surface flow. Less baseflow results in a decrease in cold water inputs for streams from the groundwater aquifer, often resulting in increased stream temperatures during the summer and colder stream temperatures in the winter for temperate streams, the magnitude being generally driven by the local climate conditions.

Aquifer recharge rates are known to vary depending on land cover: the type of land cover in a watershed influences the levels of water evapotranspiration to the atmosphere, percolation and recharge to the groundwater aquifer, and surface runoff to the stream (Dunne & Leopold 1978). According to the International Soil and Water Assessment tool (Neitsch et al. 2005), grasslands generate the highest aquifer recharge rates followed by, in descending order of recharge contribution, forest, croplands and industrial/commercial land cover classifications. Thus, alteration of upland land cover within a watershed can impact the thermal regime of stream ecosystems, altering the amount of brook charr habitat (Dunne & Leopold 1978; Bartholic et al. 1983; Wang et al. 2006; Gaffield et al. 2005; Stranko et al. 2008).

Hudy et al. (2008) used landscape variables to predict the status of self-sustaining brook charr populations throughout their historic eastern U.S. range (Maine to Georgia) as part of the Eastern Brook Trout [charr] Joint Venture (EBTJV). In this analysis, all subwatersheds in the eastern native range were classified as having intact (50–99% streams in subwatershed had self-sustaining brook charr populations), reduced (<50%) or extirpated (0%) brook charr populations with presence or absence being related to 80 known physical, chemical and biological drivers of brook charr population dynamics (Hudy et al. 2008). From these results, a classification tree methodology was applied, which isolated five core landscape metrics significant to brook charr population status (Table 1). These five core metrics were then used to create a model to predict the status of brook charr in all

Table 1. Core metrics used to classify eastern brook charr subwatershed status (adapted from Hudy et al. 2008).

Core metric
Sulphate and nitrate deposition in the subwatershed
Percentage mixed forest lands in the water corridor
Road density
Per cent forest cover in the subwatershed
Per cent agriculture in the subwatershed

unknown subwatersheds. Two of the five core metrics determined by Hudy et al. (2008) were upland land cover variables. Per cent forest cover in the subwatershed was positively correlated with intact brook charr populations while per cent agriculture in the subwatershed was negatively correlated with intact population status for these eastern U.S. brook charr populations.

Agriculture was determined to be the most widespread negative factor affecting brook charr in the eastern U.S. range (Hudy et al. 2005), with 12% agricultural land use within the subwatershed being identified as a threshold value for intact subwatersheds (Hudy et al. 2008). In other words, subwatersheds composed of <12% agriculture were more likely to contain intact populations of brook charr compared to subwatersheds with greater agricultural land use. A second threshold value predicted that upland forest cover in a watershed below 65–70% resulted in reduced brook charr populations (Hudy et al. 2008). The streams evaluated in the EBTJV were principally found in the Appalachian Mountain Chain and therefore have different geology and groundwater dynamics when compared to the streams in the Upper Midwest. As such, we were interested in evaluating whether eastern land cover threshold values were valid for brook charr in the predominantly lower elevation, sandy streams typically found in the Upper Midwest of the U.S. The goal of this study was to evaluate the relationship between groundwater input and upland land cover associated with brook charr streams, particularly in regards to the amount of forest cover and agricultural land use between the eastern and upper midwestern United States.

Methods

To evaluate land cover composition in Upper Midwest watersheds that contained brook charr, we compiled data on all known brook charr streams in Michigan and Wisconsin from the National Fish Habitat Action Plan (NFHAP) database (Esselman et al. in press). This database is an inventory of every confluence-to-confluence stream reach in the conterminous United States, linked to landscape and hydrologic data associated with each catchment. Catchments were delineated using the National Hydrography Dataset Plus (1:100,000 scale; USGS (United States Geological Survey) 2006), the same database used by Hudy et al. (2008) to identify subwatersheds in the EBTJV. We isolated 1701 stream reaches with confirmed brook charr presence in the states of Michigan and Wisconsin. The NFHAP land cover data are based off of the National Land Cover Dataset 2001(Homer et al. 2007). The satellite-derived, 30-metre grid coverages were reclassified into forest (sum percentages of deciduous, evergreen, mixed forest types), developed (residential, industrial land use), grass/shrubland, agriculture (crops), wetland (woody, nonwoody) and open water to compare our results to threshold values proposed by Hudy et al. (2008) for the East. Furthermore, our supposition was that stream temperatures in this region were determined in large part by the contribution of groundwater to the total flow, and therefore, per cent annual baseflow was analysed as a function of groundwater input for all brook charr streams. The annual baseflow volume was estimated from U.S. Geological Survey streamgage data (Wolock 2003). This comparison of per cent groundwater between the midwestern and eastern regions of the brook charr range was possible with an evaluation of summer ambient air temperature conditions. We found that air temperatures were comparable for each region thereby minimising the climatic effects associated with ambient air conditions in midsummer (Fig. 2), a time when stream temperatures would be their warmest.

In addition to the overall evaluation of the Upper Midwest land cover and annual baseflow, we selected

Fig. 2. Annual mean daily average air temperatures in August for the eastern and midwestern United States [adapted from National Climatic Data Center (NCDC) 2005].

six reported high-quality brook charr streams to perform a more detailed analysis of brook charr streams having different land cover and baseflow to assess the potential role of these drivers in maintaining productive brook charr populations: three in the Upper Midwest and three in the eastern U.S. brook charr range (Fig. 1). Through fisheries assessment surveys and personal communication with state and federal fisheries managers, the streams selected in each of these regions were known to have consistently high, natural production of brook charr. The three subwatersheds from the eastern range were classified as intact, based on the analysis by Hudy et al. (2008). Brook charr populations in the Midwest lack EBTJV classifications and therefore Minnesota, Wisconsin and Michigan streams were chosen because they were designated by state management agencies as having natural production high enough to support a vibrant recreational fishery (MNDNR (Minnesota Department of Natural Resources) 2010; WDNR (Wisconsin Department of Natural Resources) 2002; Zorn & Sendek 2001). Because of their robust brook charr populations, the selected streams were assumed to provide similar cold water conditions and therefore allowed comparisons between the two regions with respect to land cover and per cent annual baseflow.

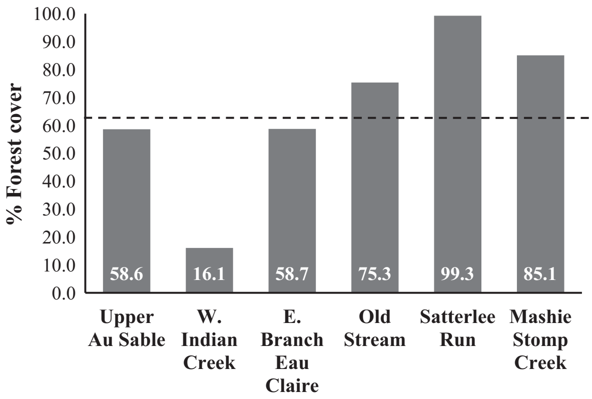

Fig. 3. Per cent (%) total forest cover in subwatersheds of six study sites in the U.S. native brook charr range having productive intact populations. Hudy et al. (2008) proposed threshold value of at least 65% forest cover (dashed line) for intact eastern brook charr streams.

Results

Of the 1701 subwatersheds evaluated in the Upper Midwest, 1098 were found to have agricultural land use levels greater than the 12% threshold proposed for this land cover type in the East (Hudy et al. 2008). In the catchments surrounding brook charr streams in this region, there was an average of 24.1% of the catchment dedicated to agriculture, with some catchments having as high as 92% agricultural land use. A summary of this land cover composition analysis can be found in Table 2. The average per cent forest cover in Michigan and Wisconsin was 44.6%, with 1346 of the 1701 subwatersheds having forest cover levels less than the threshold value (65%)for intact eastern brook charr subwatersheds. Annual per cent baseflow in the midwestern streams studied ranged from 35% to 88% and averaged 63%, a value that is cited by Raleigh (1982) as providing excellent thermal conditions for brook charr production.

Of the six high-quality brook charr streams evaluated, all of the Upper Midwest subwatersheds had total forest cover below the 65% threshold value identified by the EBTJV analysis (Fig. 3). Conversely, all three of the subwatersheds in the East had forest cover >75% and agricultural land use <3%. Agricultural land use in the East Branch of the Eau Claire watershed in Wisconsin (15.2%) and West Indian Creek in Minnesota (44.9%) exceeded the 12% threshold value which predicted reduced brook charr populations in the East (Fig. 4). Developed land cover for residential and industrial use was below 9% for all subwatersheds in both regions.

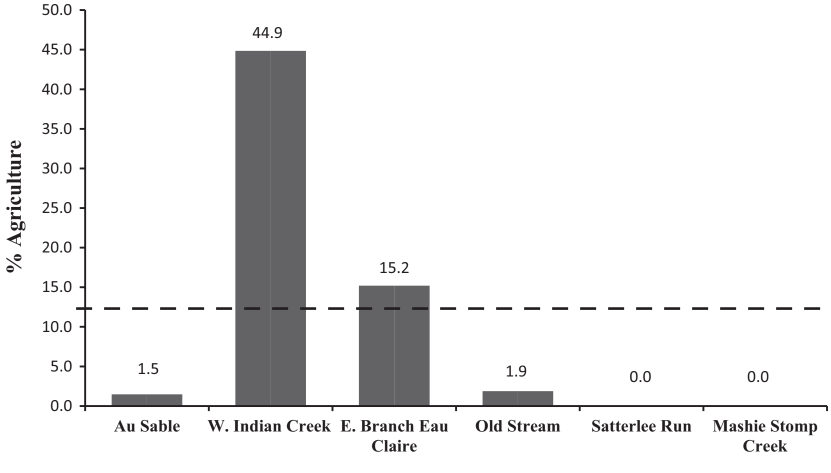

Fig. 4. Per cent (%) agriculture in subwatersheds of six study sites in the U.S. native brook charr range having intact populations. Hudy et al. (2008) proposed threshold value not more than 12% (dashed line) for intact eastern brook charr streams.

Table 2. Land cover for 1701 brook charr stream catchments in the Upper Midwest states of Michigan and Wisconsin, U.S.A. Based on National Land Cover Dataset 2001 (Homer et al. 2007).

% Cover type	Average	Maximum	Standard deviation
Agriculture	24.1	91.7	20.5
Developed	7.1	94.4	8.6
Forest	44.6	100.0	23.3
Shrub/Scrub	1.3	15.8	1.9
Grass/Herbaceous	3.4	51.7	5.9
Wetlands	9.7	100.0	13.3

The different hydrologic characteristics of the two regions (Table 3) allowed further analysis of the acting thermal drivers in these brook charr streams. Baseflow estimates for Old Stream, Mashie Stomp Creek, the Upper Au Sable, East Branch of the Eau Claire and West Indian Creek were all considered excellent for brook charr production based on the species' habitat suitability index (Raleigh 1982). Satterlee Run, a second-order stream in Pennsylvania whose catchment was almost solely forest cover (99%), was found to be a surface water–dominated stream. In North Carolina, brook charr populations are generally restricted to higher elevation streams (Flebbe 1994). Elevation appeared to be important as a modifier of ambient air temperatures and thus water temperatures for the more southern stream, Mashie Stomp Creek.

Discussion

As depicted by our results, the Upper Midwest catchments studied fell outside the threshold values proposed by Hudy et al. (2008) for maintaining intact brook charr status based on their eastern U.S. distribution. The relatively large percentage of agricultural land and reduced forest cover found in the midwestern brook charr catchments would cause the EBTJV model (Hudy et al. 2008) to incorrectly predict the status of many Upper Midwest watersheds. For instance, streams such as the West Indian Creek in Minnesota which had a high per cent agriculture would be considered unacceptable for brook charr populations by the EBTJV model when in fact this stream supports a highly productive natural brook charr population. While land cover models provide an efficient way for managers to predict fish distribution and their relative productivity, we believe that groundwater discharge is the key thermal driver that allows for intact brook charr populations to exist in these subwatersheds with reduced forest cover or high agricultural land use in the Upper Midwest of the United States. When groundwater is not the primary source of stream flow, other cold water drivers must exist if thermal conditions are to be suitable for brook charr, including land cover that keeps waters cool or climatic temperatures which stay in the range of temperatures that allow for brook charr populations to exist. For instance, land cover changes that occur in catchments with less permeable soils or steep terrain may result in deficient aquifer recharge needed to regulate stream temperature for brook charr. Under these conditions, high-elevation cold air temperatures or relatively high amounts of forest cover become imperative to limit the heating of surface water within the subwatershed to maintain brook charr thermal habitat. This is especially true for streams such as high-elevation Mashie Stomp Creek (North Carolina) and heavily forested catchment of Satterlee Run (Pennsylvania) in our study. Streams dominated by surface water or low volume streams are particularly susceptible to warming from ambient air temperature in climates that surpassed temperature ranges suitable for brook charr production. It is generally the forest canopy that regulates the microclimate surrounding these streams, thus protecting vulnerable streams in warm climates (Stranko et al. 2008; Booth et al. 2002). Satterlee Run provides an excellent example of this phenomenon because, according to the baseflow estimate, this stream receives the majority of its flow from surface water input. Therefore, without shade from the extensive forest cover throughout the catchment, this stream would likely be too warm to support brook charr. Figure 5 depicts a simple schematic of how baseflow and ambient air temperature must balance to produce thermal habitat suitable to brook charr. Land cover changes have the potential to affect both of these parameters as shown by this study and the EBTJV model.

West Indian Creek (MN), with 45% agriculture and 16% forest cover in the catchment, had a pronounced divergence from the threshold values reported for per cent forest cover and agriculture from the EBTJV model. However, based on the relatively high amount of baseflow in this stream (65%), the groundwater aquifer supplied this stream with water temperatures that can support brook charr populations throughout

Table 3. Comparison of hydrologic characteristics for six high-quality brook charr streams across native U.S. range.

Stream name	Upper Au Sable	W. Indian Creek	E. Branch Eau Claire	Old Stream	Satterlee Run	Mashie Stomp Creek
State	Michigan	Minnesota	Wisconsin	Maine	Pennsylvania	North Carolina
Minimum elevation (m)	106.7	67.9	133.9	7.3	86.4	364.0
Stream order	2	3	2	4	2	1
Annual baseflow (%)	77	65	70	56	37	65

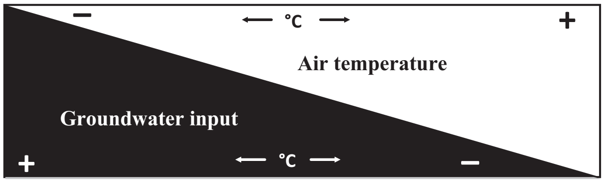

Fig. 5. The thermal trade-off in streams necessary to achieve a constant water temperature. For brook charr, less groundwater input must be mitigated by cooler air temperatures if water temperature is to stay within livable thermal range.

the year. We believe that the low-gradient topography and coarse surficial geology of intact brook charr subwatersheds in the Upper Midwest are conducive to high precipitation absorption and percolation into the groundwater aquifer, allowing for consistent cold water delivery. Our conclusions are consistent with other studies in Upper Midwest watersheds such as those by Waco & Taylor (2010) who found that conversion of forest to pasture would result in very minor shifts in stream temperature. Their study site was characterised by low-elevation, sand and gravel soils with high percolation rates and low surface water runoff. Despite land cover alteration, the cumulative effects of low-gradient topography and coarse surficial geology allowed the groundwater aquifer to recharge at relatively high rates, thereby providing the cold thermal habitat in local streams needed by resident brook charr (Waco & Taylor 2010).

Management implications

Thresholds are not universal, and managers must be cautious about setting land use goals for fisheries without consideration to the regional hydrologic dynamics and climate conditions. Identification of the key mechanisms controlling cold water delivery and maintenance in brook charr streams is a fundamental step in the effective management of this cold water–reliant species. The threats to brook charr populations should be prioritised based on the impact these changes have on cold water delivery systems to streams. Increasing human demand for land and freshwater resources threatens U.S. brook charr populations by compromising the cold water habitat necessary for sustained productivity of this species. In groundwater-dominated brook charr streams, it is imperative to evaluate the effects of aquifer withdrawal for human use in the light of brook charr production (Waco & Taylor 2010). Dams and stream channelisation also have the potential to negatively affect brook charr populations by altering temperature regimes (Ward & Stanford 1983) and by fragmenting migration corridors when local temperatures become unfavourable. Coupled with these potential changes to the thermal regimes of our river systems is the threat from climate change which has been predicted to have significant influence on the regional distribution and local extent of salmonid habitat worldwide (Meisner 1990; Keleher & Rahel 1996). To mitigate these effects, the landscape will need to be managed for high groundwater recharge rates and limited surface water heating if eastern and midwestern U.S. brook charr populations are to be conserved. Managing aquatic systems in the context of terrestrial landscapes is important to adequately manage fish and fisheries (Taylor et al. 2002). The linkage between the landscape and lotic systems enables fisheries researchers and managers to identify patterns in land cover and stream thermal regime as these variables pertain to brook charr population distribution and their production dynamics. Ultimately, communication between land, water and fisheries managers is needed for prioritisation of brook charr protection and restoration efforts based on unique regional characteristics affecting cold water delivery these salmonid streams.

Acknowledgements

We thank our funding support from Andrea Ostroff and the United States Geological Survey, along with the College of Agriculture and Natural Resources and the Graduate School at Michigan State University. Furthermore, we thank Dana Infante, Peter Esselman, Arthur Cooper and Darren Thornbrugh for providing support and access to National Fish Habitat Action Plan database.

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